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Daigle

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(54) **SYSTEM AND METHOD FOR TRACTION MOTOR CONTROL**

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B61C 15/08 (2006.01)
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CPC ***H02P 23/0063*** (2013.01); ***B60L 3/102*** (2013.01); ***B60L 3/104*** (2013.01); ***B60L 11/08*** (2013.01); ***B60L 15/2063*** (2013.01); ***B61C 15/12*** (2013.01); *B60L 2200/26* (2013.01); *B60L 2220/46* (2013.01); *B60L 2240/12* (2013.01); *B60L 2240/421* (2013.01); *B60L 2240/423* (2013.01); *B60L 2240/429* (2013.01); *B60L 2240/461* (2013.01); *B60L 2240/463* (2013.01); *B60L 2240/465* (2013.01); *B60L 2260/28* (2013.01); *Y02T 10/642* (2013.01); *Y02T 10/70* (2013.01); *Y02T 10/7077* (2013.01); *Y02T 10/7275* (2013.01); *Y02T 30/10* (2013.01)

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USPC 318/52, 400.09, 400.3, 139, 430, 434, 318/801–803, 811
See application file for complete search history.

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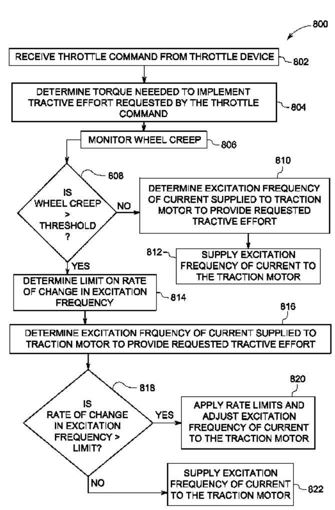
(57) **ABSTRACT**

A control method includes monitoring changes in torque produced by a traction motor when an excitation frequency of current supplied to the traction motor changes, determining if the torque produced by the traction motor decreases when the excitation frequency of the current supplied to the traction motor increases, and responsive to the torque produced by the traction motor decreasing when the excitation frequency increases, preventing the excitation frequency of the current supplied to the traction motor from increasing further.

20 Claims, 10 Drawing Sheets



(51) **Int. Cl.**

H02P 23/00	(2006.01)
B61C 15/12	(2006.01)
B60L 3/10	(2006.01)
B60L 11/08	(2006.01)
B60L 15/20	(2006.01)

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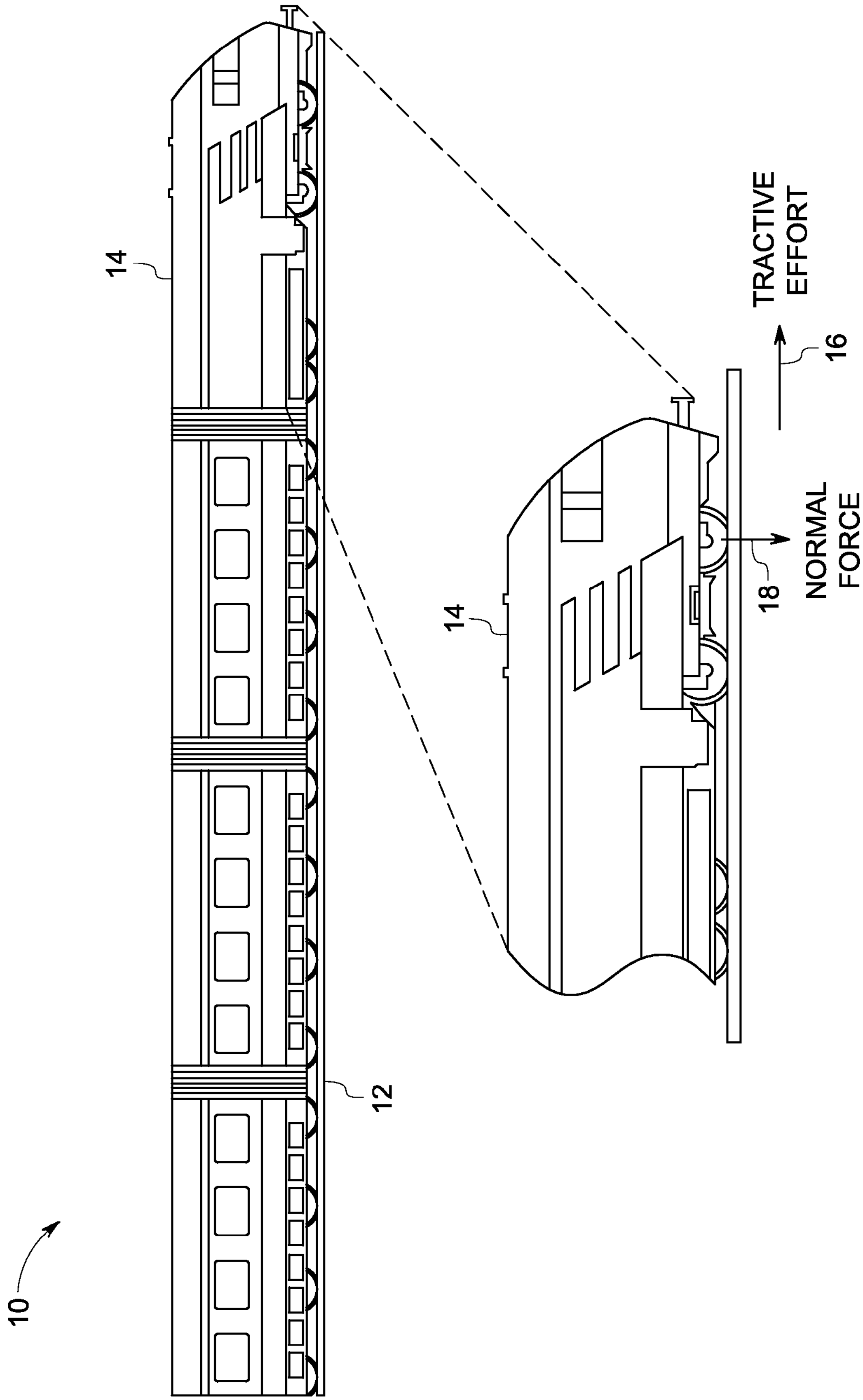


FIG. 1

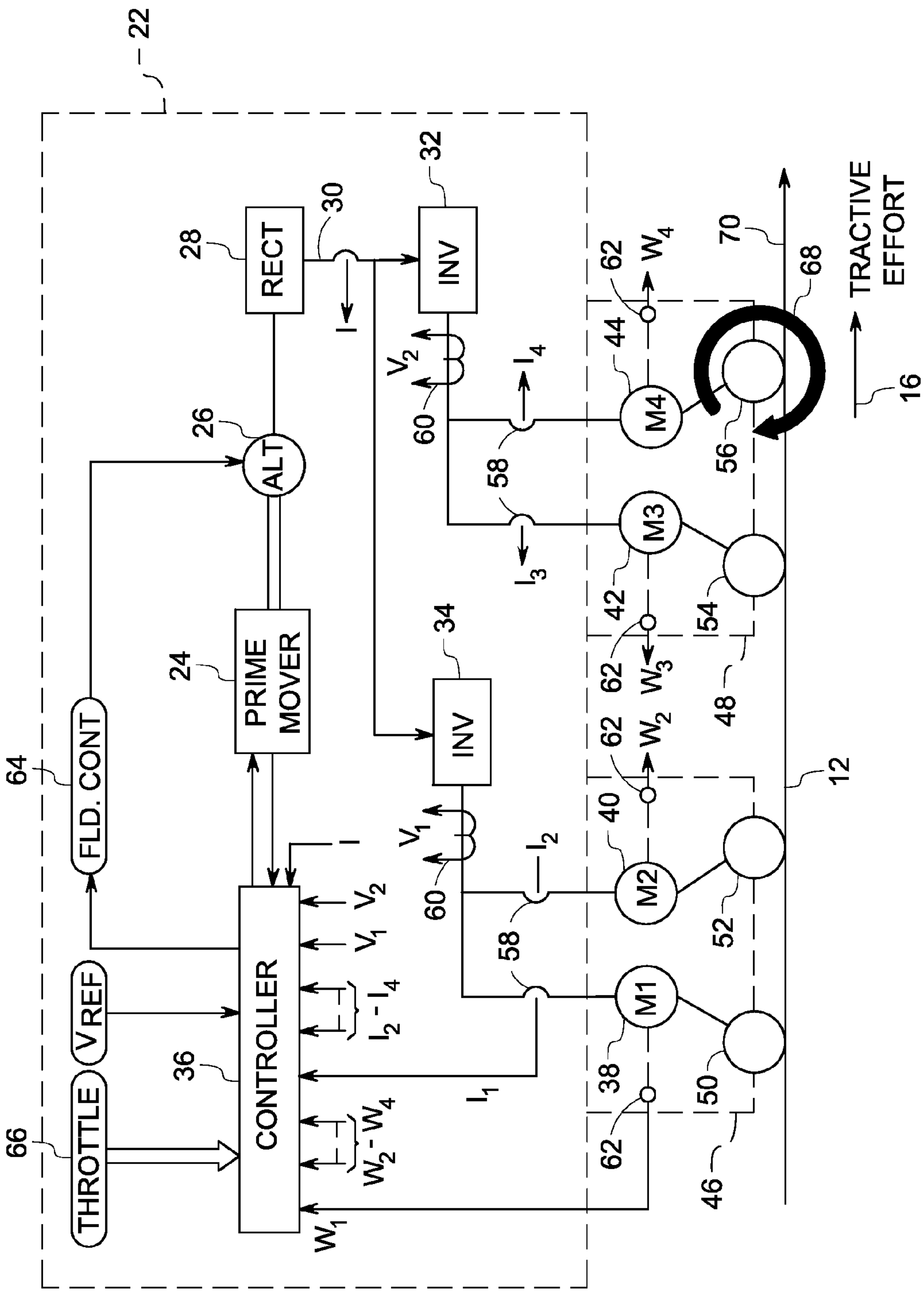

22
THROTTLE
VREF
FLD. CONT
CONTROLLER
PRIME MOVER
ALT
RECT
INV
INV
M1
M2
M3
M4
TRACTIVE EFFORT
W_1
W_2-W_4
I_2-I_4
V_1
V_2
I_1
I_2
I_3
I_4
I
W_2
W_3
W_4
12
16
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
60
62
64
66
68
70

FIG. 2

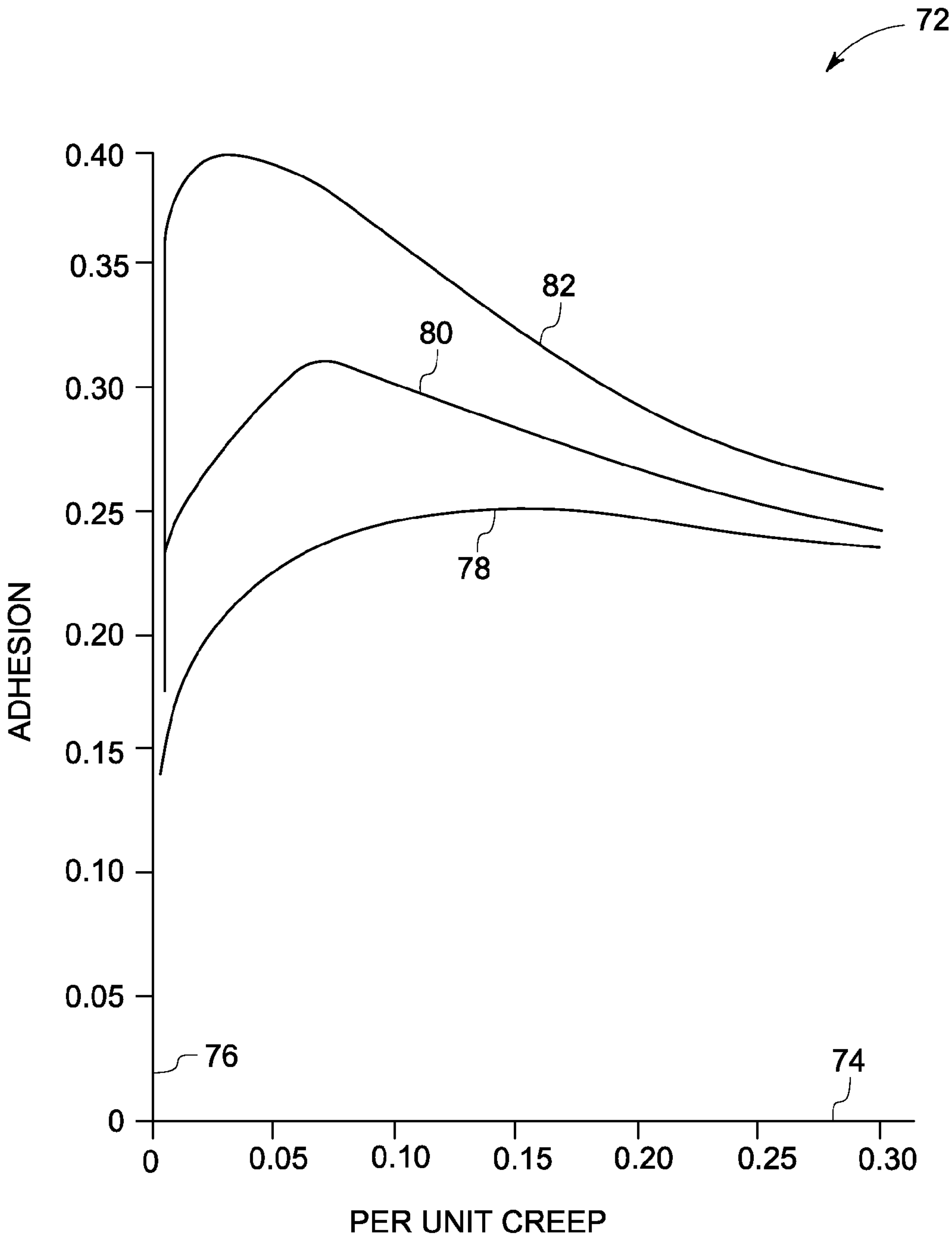
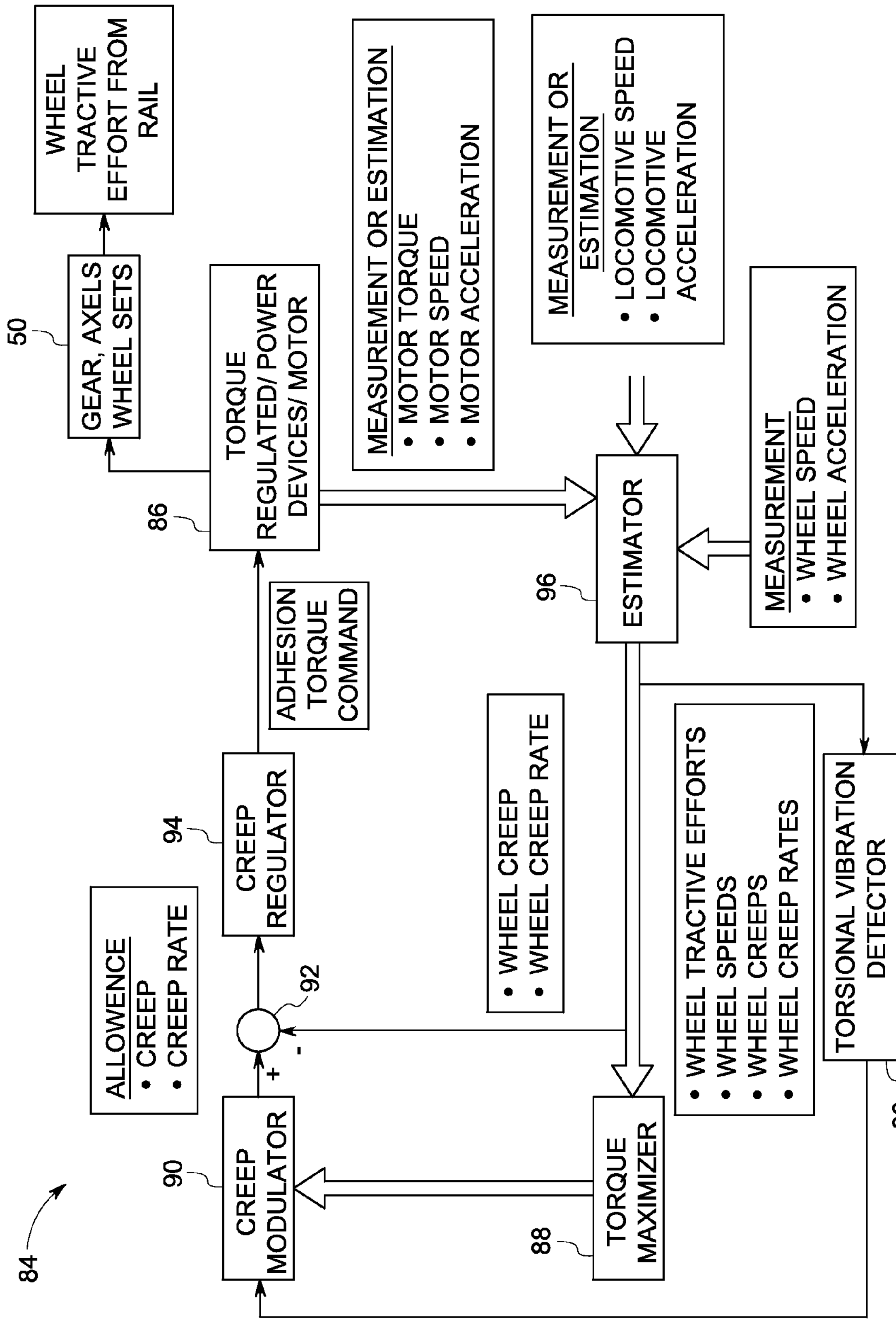

72
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
ADHESION
82
80
78
76
74
0
0.05
0.10
0.15
0.20
0.25
0.30
PER UNIT CREEP

FIG.3



WHEEL TRACTIVE EFFORT FROM RAIL
50
GEAR, AXELS WHEEL SETS
86
TORQUE REGULATED/ POWER DEVICES/ MOTOR
MEASUREMENT OR ESTIMATION
• MOTOR TORQUE
• MOTOR SPEED
• MOTOR ACCELERATION
MEASUREMENT OR ESTIMATION
• LOCOMOTIVE SPEED
• LOCOMOTIVE ACCELERATION
96
ESTIMATOR
MEASUREMENT
• WHEEL SPEED
• WHEEL ACCELERATION
ADHESION TORQUE COMMAND
94
CREEP REGULATOR
ALLOWENCE
• CREEP
• CREEP RATE
92
+
-
• WHEEL CREEP
• WHEEL CREEP RATE
• WHEEL TRACTIVE EFFORTS
• WHEEL SPEEDS
• WHEEL CREEPS
• WHEEL CREEP RATES
TORSIONAL VIBRATION DETECTOR
98
84
90
CREEP MODULATOR
88
TORQUE MAXIMIZER

FIG. 4

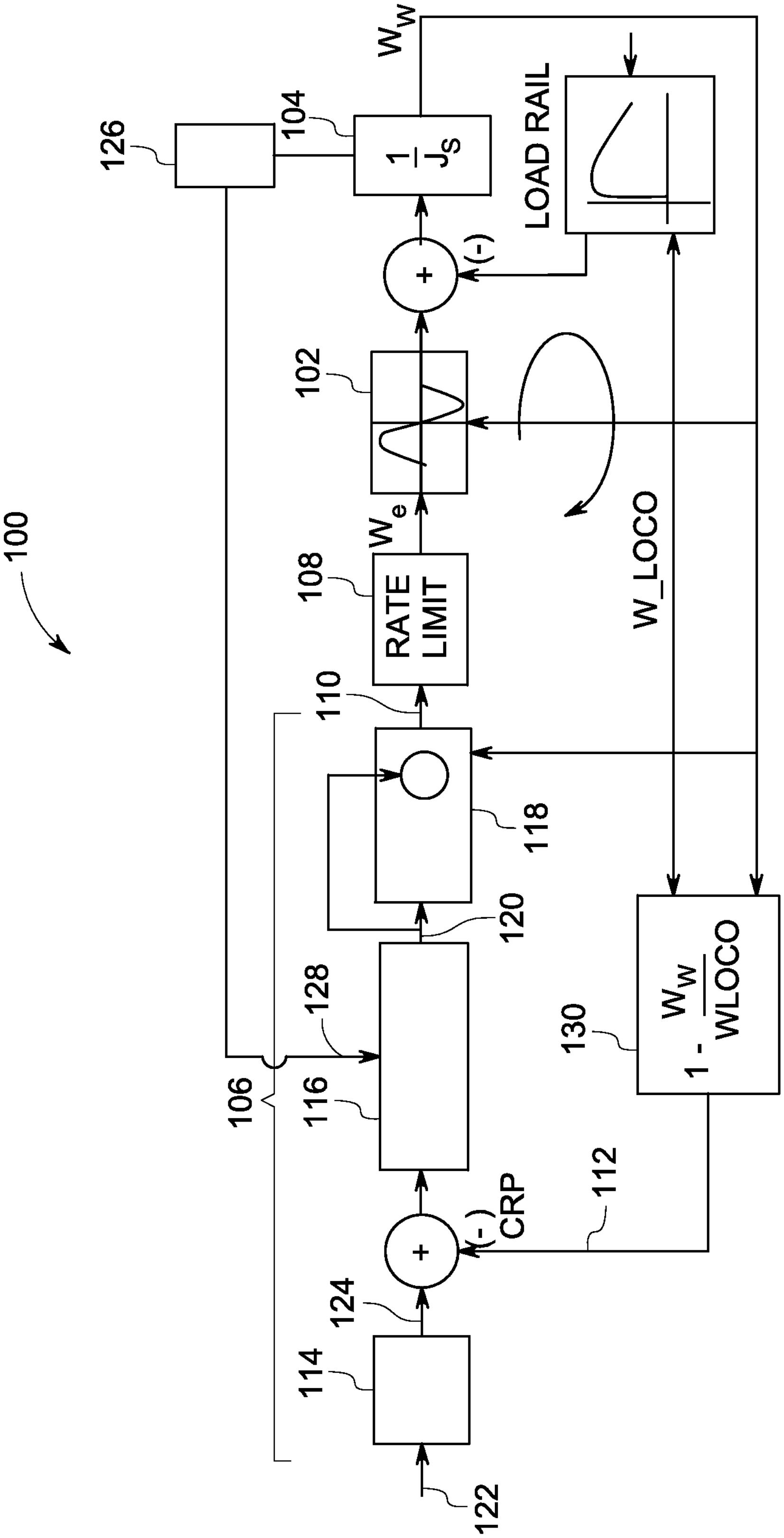

100
126
104
W_W
$\frac{1}{J_S}$
LOAD RAIL
(-)
102
108
RATE LIMIT
W_e
W_LOCO
110
118
120
128
106
116
130
$1 - \frac{W_W}{WLOCO}$
112
CRP
(-)
124
114
122

FIG. 5

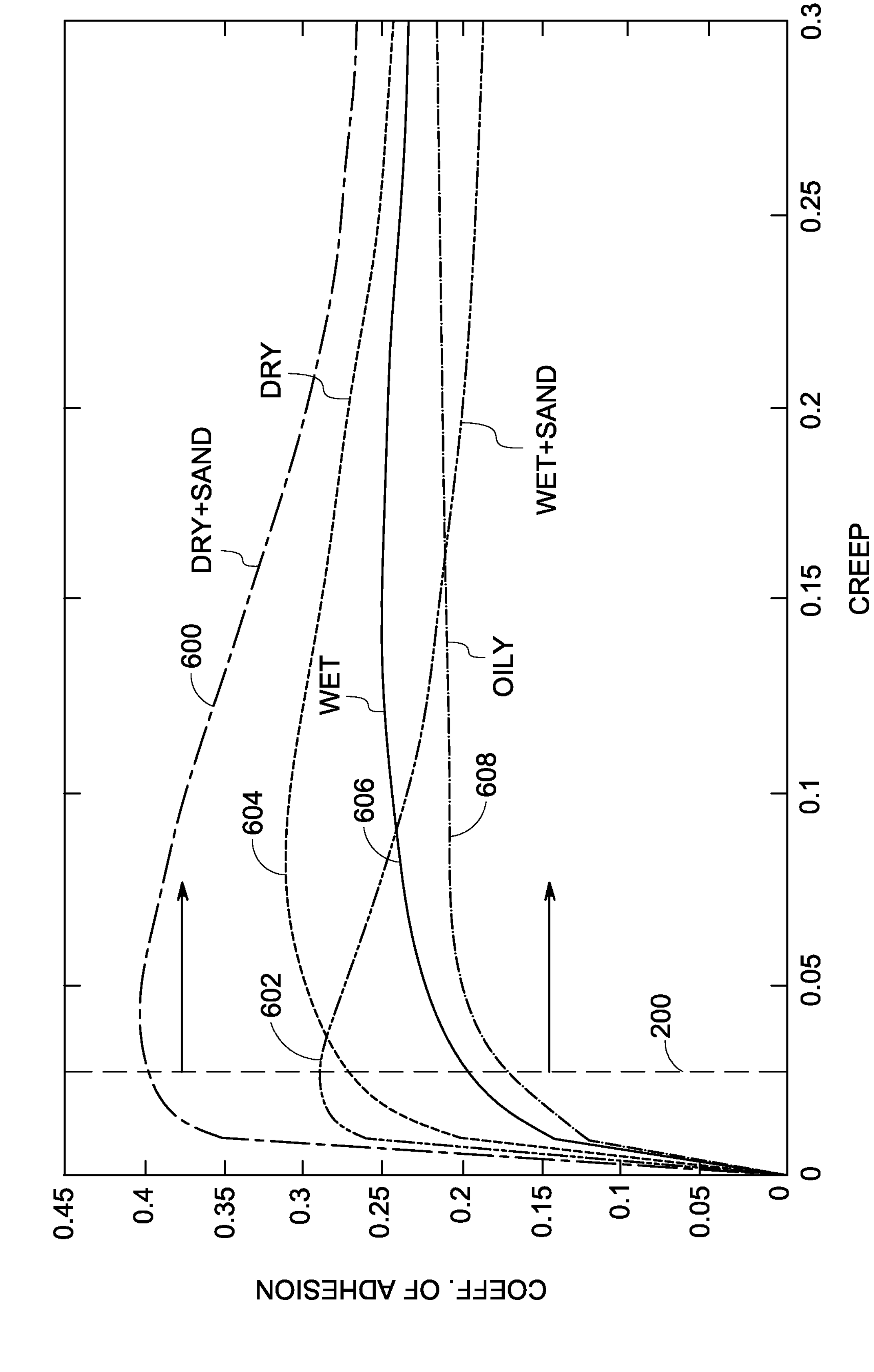

COEFF. OF ADHESION
CREEP
DRY+SAND
DRY
WET
OILY
WET+SAND
600
602
604
606
608
200
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45

FIG. 6

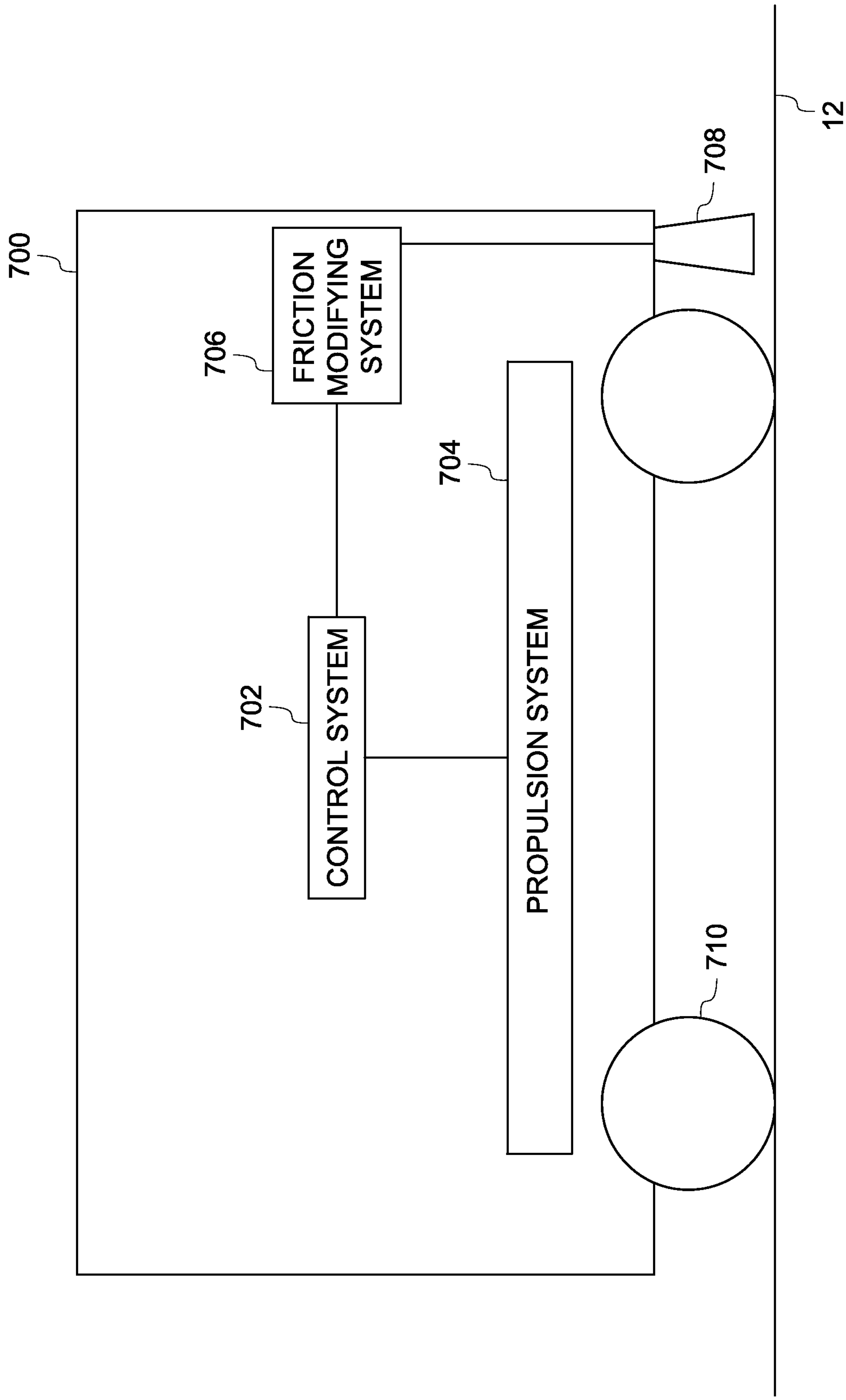

700
706
FRICTION MODIFYING SYSTEM
708
12
704
702
CONTROL SYSTEM
PROPULSION SYSTEM
710

FIG. 7

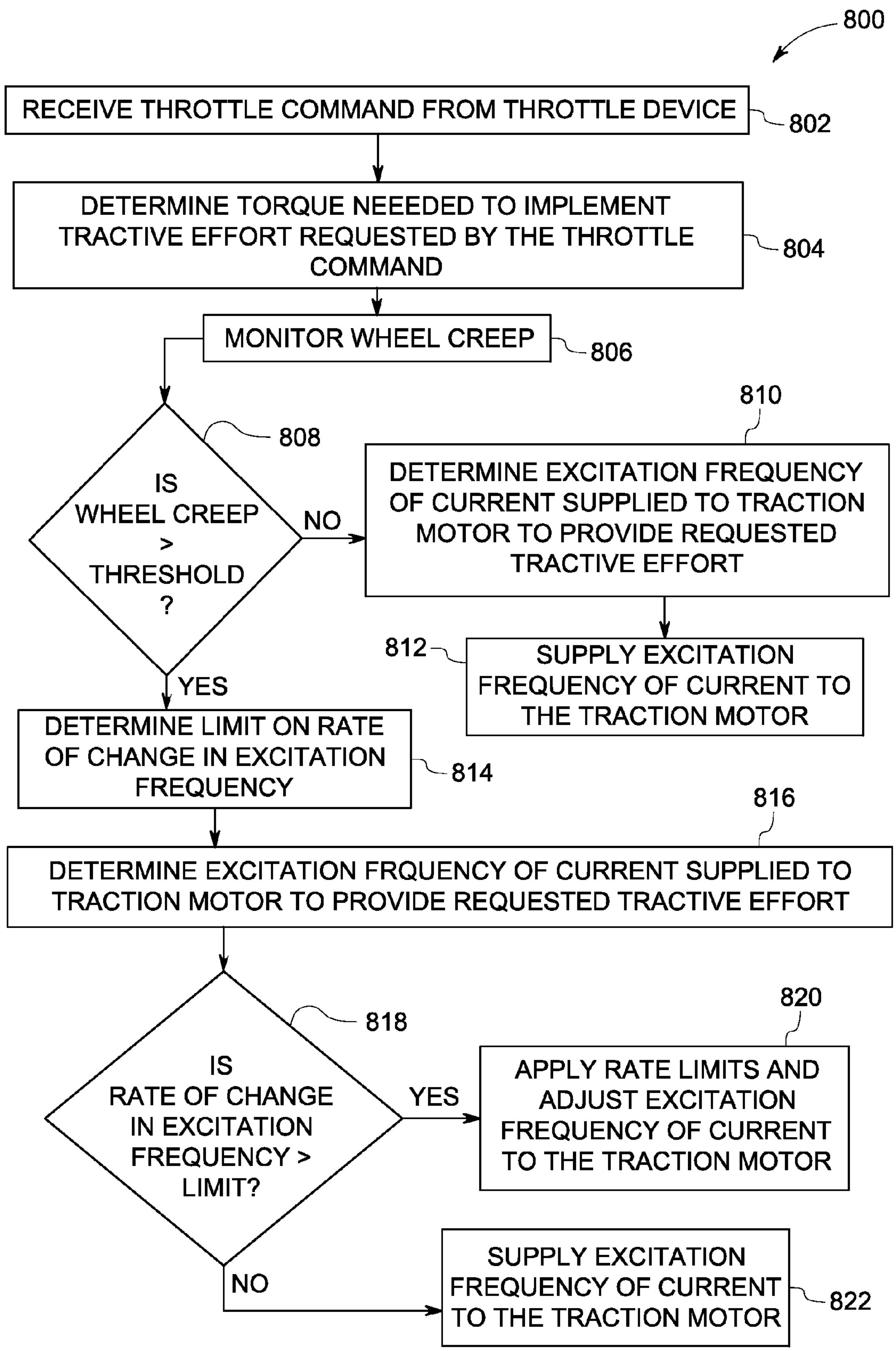

800
RECEIVE THROTTLE COMMAND FROM THROTTLE DEVICE
802
DETERMINE TORQUE NEEEDED TO IMPLEMENT TRACTIVE EFFORT REQUESTED BY THE THROTTLE COMMAND
804
MONITOR WHEEL CREEP
806
IS WHEEL CREEP > THRESHOLD ?
808
NO
DETERMINE EXCITATION FREQUENCY OF CURRENT SUPPLIED TO TRACTION MOTOR TO PROVIDE REQUESTED TRACTIVE EFFORT
810
SUPPLY EXCITATION FREQUENCY OF CURRENT TO THE TRACTION MOTOR
812
YES
DETERMINE LIMIT ON RATE OF CHANGE IN EXCITATION FREQUENCY
814
DETERMINE EXCITATION FRQUENCY OF CURRENT SUPPLIED TO TRACTION MOTOR TO PROVIDE REQUESTED TRACTIVE EFFORT
816
IS RATE OF CHANGE IN EXCITATION FREQUENCY > LIMIT?
818
YES
APPLY RATE LIMITS AND ADJUST EXCITATION FREQUENCY OF CURRENT TO THE TRACTION MOTOR
820
NO
SUPPLY EXCITATION FREQUENCY OF CURRENT TO THE TRACTION MOTOR
822

FIG. 8

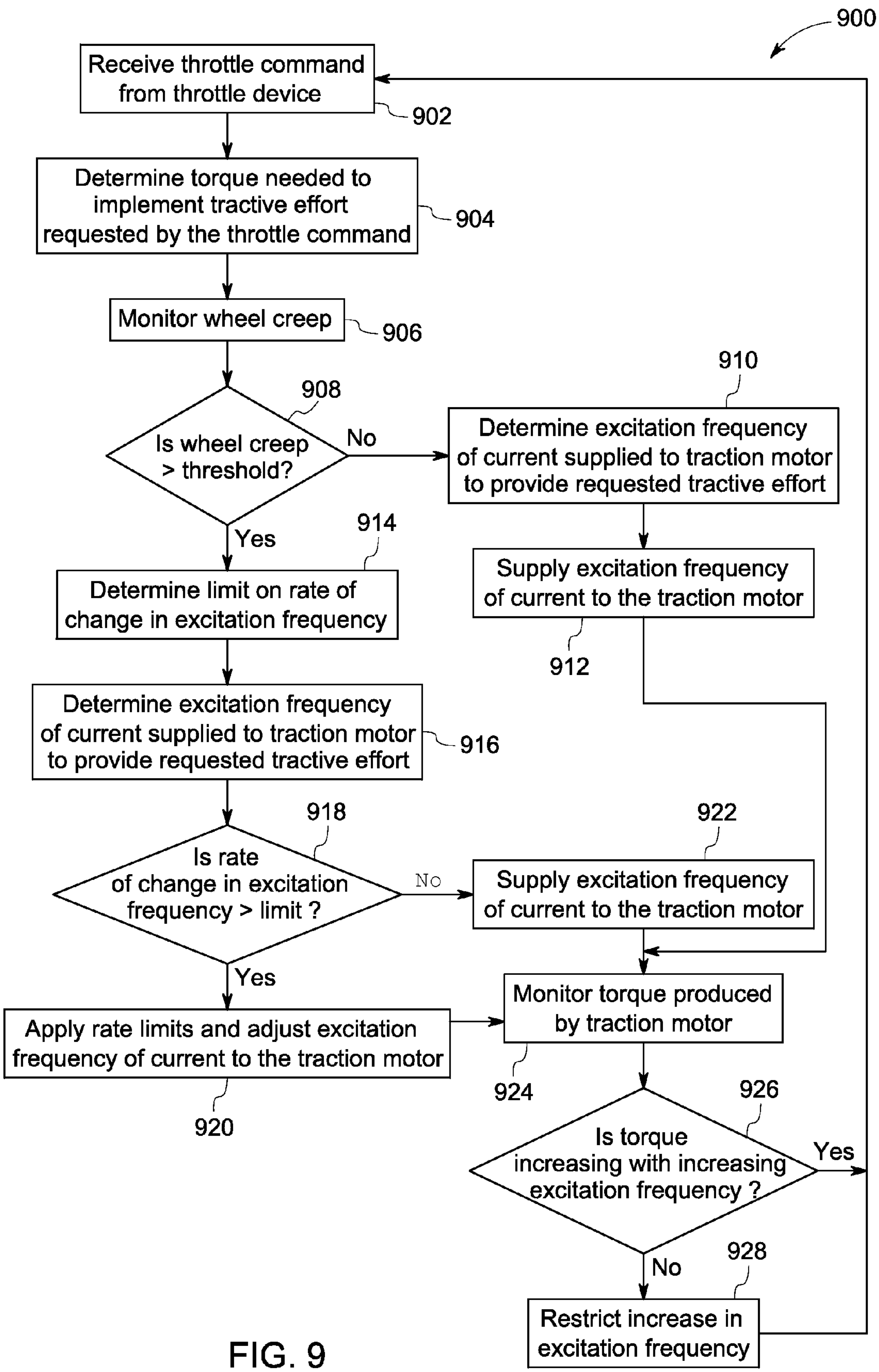

900
Receive throttle command from throttle device
902
Determine torque needed to implement tractive effort requested by the throttle command
904
Monitor wheel creep
906
908
Is wheel creep > threshold?
No
910
Determine excitation frequency of current supplied to traction motor to provide requested tractive effort
Yes
914
Determine limit on rate of change in excitation frequency
Supply excitation frequency of current to the traction motor
912
Determine excitation frequency of current supplied to traction motor to provide requested tractive effort
916
918
Is rate of change in excitation frequency > limit ?
No
922
Supply excitation frequency of current to the traction motor
Yes
Apply rate limits and adjust excitation frequency of current to the traction motor
Monitor torque produced by traction motor
924
920
926
Is torque increasing with increasing excitation frequency ?
Yes
No
928
Restrict increase in excitation frequency

FIG. 9

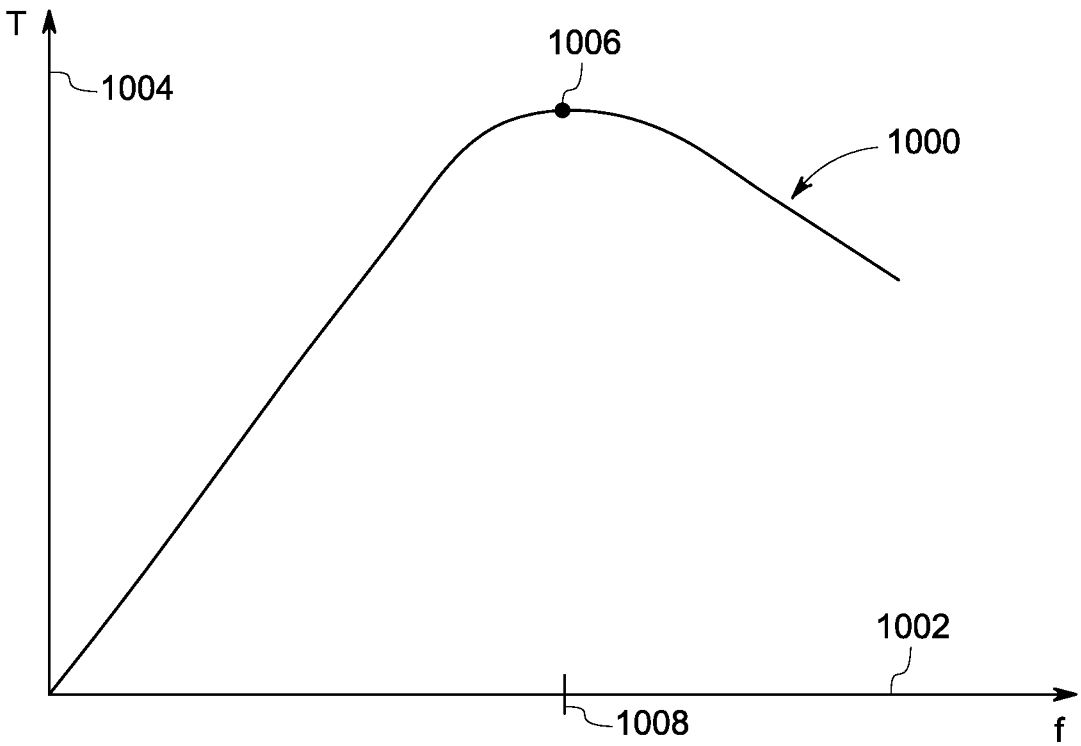


FIG. 10

SYSTEM AND METHOD FOR TRACTION MOTOR CONTROL

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. application Ser. No. 13/632,320, filed Oct. 1, 2012, which claims priority to U.S. Provisional Application Ser. No. 61/542,796, filed Oct. 3, 2011, the entire disclosures of which are incorporated by reference.

FIELD

Embodiments of the inventive subject matter described herein relate to motor control. Other embodiments relate to traction motor control in a vehicle.

BACKGROUND

Certain rail vehicles (e.g., locomotives) and other off-highway vehicles are powered by electric traction motors coupled in driving relationship to one or more axles of the vehicle. In a motoring mode of operation, the traction motors are supplied with electric current from a controllable source of electric power such as an engine-driven traction alternator. The traction motors apply torque to the vehicle wheels, which in turn exert tangential force (tractive effort) on the surface on which the vehicle is traveling, e.g., the parallel steel rails of a railroad track, and thereby propel the vehicle in a desired direction along a route of travel. In another instance, in a dynamic braking mode of operation, the motors serve as axle-driven electrical generators. In this mode of operation, the traction motors exert torque in an opposite direction from the rolling direction of the wheels, thereby slowing the vehicle's motion. In either case, good adhesion between each wheel and the surface facilitates efficient operation of the vehicle.

Maximum tractive effort or braking effort is obtained if each powered wheel of the vehicle is rotating at such an angular velocity that its actual peripheral speed (e.g., wheel speed) is slightly higher (in case of motoring) or slightly lower (in case of braking) than the actual speed of the vehicle. The difference between the linear speed at which the vehicle is traveling (referred to as ground speed) and wheel speed is referred to as slip speed, creep, or wheel creep. There is usually a relatively low limit on the value of slip speed at which peak tractive effort or braking effort is realized. This value, commonly known as optimum creep, is a variable that depends on ground speed and travel surface conditions. Operation of any or all wheels away from the optimum creep, e.g., at too small a creep value or too large a creep value, may result in a reduction or loss of wheel-to-surface adhesion. Likewise, if the wheel-to-surface adhesion tends to be reduced or lost, some or all the vehicle wheels may slip excessively, i.e., the actual slip speed or creep may be greater than the optimum creep. Such a wheel slip condition, which is characterized in the motoring mode by one or more slipping axle-wheel sets and in the braking mode by one or more sliding or skidding axle-wheel sets, can cause accelerated wheel wear, rail damage, high mechanical stresses in the drive components of the propulsion system, and an undesirable decrease of tractive (or braking) effort.

Wheel creep may be controlled using creep regulators. However, especially at low speeds, creep regulators have an increasingly more difficult time regulating wheel speeds. This leads to large overshoots in wheel speed, rapid torque reductions, and torque reapplication limit cycles. This may result in high wheel creep transients capable of damaging the rail head (in the case of a rail vehicle), reduced tractive effort, rapid suspension displacements, poor vehicle ride quality, and vehicle reference speed errors.

BRIEF DESCRIPTION

In an embodiment, a control method includes monitoring changes in torque produced by a traction motor when an excitation frequency of current supplied to the traction motor changes, determining if the torque produced by the traction motor decreases when the excitation frequency of the current supplied to the traction motor increases, and responsive to the torque produced by the traction motor decreasing when the excitation frequency increases, preventing the excitation frequency of the current supplied to the traction motor from increasing further. This excitation frequency may be the excitation frequency of the voltage and the resultant current that is supplied to the motor.

In an embodiment, a control system (e.g., for a vehicle) includes first and second control modules. The first control module is configured to control an excitation frequency of a current supplied to a traction motor of a traction motor system, based at least in part on a throttle command and a speed associated with one of the traction motor or a wheel driven by the traction motor. The second control module is configured to monitor changes in torque produced by the traction motor when the excitation frequency changes and determine if the torque produced by the traction motor decreases when the excitation frequency increases. The second control module is configured to prevent the excitation frequency of the current supplied to the traction motor from increasing further responsive to the torque decreasing when the excitation frequency increases.

In an embodiment, a method (e.g., for controlling a vehicle) includes receiving changes to a throttle setting of a vehicle. The changes to the throttle setting change torque generated by a first traction motor in rotating a first wheel of a vehicle in order to propel the vehicle along a route. The method also includes determining excitation frequencies of electric current that is supplied to the first traction motor in order to power the first traction motor. The excitation frequencies are determined from the changes to the throttle setting of the vehicle. The method further includes monitoring changes in the torque generated by the first traction motor caused by changes in the excitation frequencies of the electric current supplied to the first traction motor and determining when increases in the excitation frequencies result in decreases in the torque generated by the first traction motor. The method also includes, responsive to determining that the increases in the excitation frequencies result in the decreases in the torque generated by the first traction motor, reducing the excitation frequencies supplied to the first traction motor.

In an embodiment, a control method comprises determining wheel creep of a wheel operably coupled to a traction motor and limiting a rate of change of an excitation frequency applied to the traction motor to drive the wheel, based on the determined wheel creep. According to one aspect, the rate of change of the excitation frequency is limited if the wheel creep exceeds a wheel creep threshold.

Another embodiment relates to a control system. The control system comprises a first control module configured to generate an excitation frequency for a traction motor system. The traction motor system includes a traction motor and a traction inverter (e.g., power electronics for converting an input voltage to one or more output signals for controllably powering the traction motor). The first control module is configured to generate the excitation frequency based at least in part on a speed and a throttle command; the speed is associated with one of the traction motor or a wheel driven by the traction motor. The control system further comprises a second control module configured to limit a rate of change of the excitation frequency responsive to a wheel creep of the wheel exceeding a wheel creep threshold.

Aspects of the inventive subject matter involve restricting the rate at which the excitation frequency to a traction motor can change once a wheel creep threshold has been exceeded. Thus, once a wheel driven by a traction motor begins to accelerate away from its creep setpoint, due to the rate limit and subsequent restriction in excitation frequency, the motor begins immediately to deliver a reduced value of accelerating torque, preventing the wheel from large creep overshoots. In effect, the gain reduction (motor torque) characteristic of the traction motor is leveraged to counter the creep gain that naturally occurs for wheeled vehicles once their wheels begin to spin (slip) or slide.

In one embodiment, a control method (e.g., for controlling a traction motor of a vehicle) includes determining wheel creep of a wheel operably coupled to the traction motor and, based on the determined wheel creep, limiting a rate of change of an excitation frequency of current that is applied to the traction motor to drive the wheel.

In one embodiment, a control method (e.g., for controlling a traction motor of a vehicle) includes determining whether wheel creep of a wheel operably coupled to the traction motor exceeds a wheel creep threshold and limiting a rate of change of an excitation frequency applied to the traction motor to drive the wheel when the wheel creep exceeds the wheel creep threshold.

In another embodiment, a control method (e.g., for controlling a traction motor of a vehicle) includes determining whether a wheel driven by the traction motor has accelerated away from a creep setpoint by at least a threshold and controlling an excitation frequency applied to the traction motor to reduce accelerating torque delivered by the motor to the wheel when the wheel has accelerated away from the creep setpoint by at least the threshold.

In one embodiment, a control system (e.g., for a vehicle having a traction motor) includes first and second control modules. The first control module is configured to generate an excitation frequency of a current supplied to a traction motor of a traction motor system, based at least in part on a throttle command and a speed associated with one of the traction motor or a wheel driven by the traction motor. The second control module is configured to limit a rate of change of the excitation frequency responsive to a wheel creep of the wheel exceeding a wheel creep threshold.

DRAWINGS

The foregoing and other advantages and features of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

FIG. **1** is diagrammatical view of a train including a locomotive, and illustrating the tractive effort and adhesion of the locomotive controlled in accordance with an embodiment of this inventive subject matter;

FIG. **2** is a diagrammatical representation of exemplary principal components of a propulsion system for a diesel-electric locomotive in accordance with aspects of the present techniques;

FIG. **3** is a graphical representation of an exemplary functional relationship between adhesion and creep for different weather conditions, illustrating optimal creep levels for adhesion;

FIG. **4** is a diagrammatical representation of an adhesion control system in which embodiments of the inventive subject matter may be implemented;

FIG. **5** is a schematic diagram of an embodiment of the inventive subject matter;

FIG. **6** is a graphical representation of various adhesion curves showing wheel creep thresholds, according to an embodiment of the inventive subject matter;

FIG. **7** is a schematic diagram of a traction vehicle in accordance with another embodiment;

FIG. **8** is a flowchart of one embodiment of a method for controlling a traction motor;

FIG. **9** is a flowchart of an embodiment of a method for controlling a traction motor; and

FIG. **10** illustrates an example of torques generated by the motor and corresponding excitation frequencies supplied to the motor.

DETAILED DESCRIPTION

Embodiments of the inventive subject matter relate to systems and methods for traction motor control in a vehicle. Onboard the vehicle is a vehicle traction system, which includes a control system and a traction motor system. The traction motor system includes a traction motor and an inverter electrically connected to the traction motor. The control system generates signals for controlling the inverter to produce power waveforms for powering the traction motor. A wheel is operably coupled to the traction motor (e.g., through a gear and/or axle set). The wheel is driven by the motor during a motoring mode of operation, and the wheel drives the motor during a dynamic or regenerative braking mode of operation. The control system also comprises a first control module and a second control module. (The modules may comprise electronic hardware and/or software, and may be part of a common controller card or similar electronics unit for motor control.) The first control module is configured to generate an excitation frequency for the traction motor system, based at least in part on a speed and a throttle command. The speed is associated with the traction motor and/or the wheel driven by the traction motor, and information of the speed may be provided by a speed sensor. The second control module is configured to limit a rate of change of the excitation frequency responsive to a wheel creep of the wheel exceeding a wheel creep threshold. Thus, once the wheel begins to accelerate away from a creep setpoint (or otherwise exhibits behavior of a forthcoming large creep overshoot, with "large" meaning an increase in creep that is over a designated magnitude), the motor is controlled (through the limit/restriction on the excitation frequency rate of change) to deliver a reduced value of accelerating torque, preventing the wheel from fully realizing the large creep overshoot.

Embodiments of the inventive subject matter are illustrated herein in regards to locomotives and other rail vehicles (e.g., in the context of a train). However, such embodiments also are applicable to off-highway vehicles or other vehicles more generally.

FIG. **1** is diagrammatical view of a vehicle system **10** including a traction vehicle **14**, and illustrating the tractive effort and adhesion of the traction vehicle **14**. The vehicle system **10** is shown and may be described herein as a train, but not all embodiments described herein are limited to trains. Additionally, the traction vehicle **14** is shown and may be described as a locomotive, but may represent another type of vehicle. The vehicle system **10** runs on a route **12**, such as a set of parallel rails of a railroad track. The traction vehicle **14** drives the vehicle system **10** using electric traction motors at each axle-wheel set, as described in greater detail below. In a motoring mode of operation, the traction motors deliver torque to the vehicle wheels, which exert tangential force (e.g., tractive effort **16**) on the route **12**, thereby propelling the vehicle system **10** along the route **12**. The tractive effort **16** developed at each wheel of the traction vehicle **14** is proportional to a normal force **18** acting on the wheel. The total tractive effort developed by the traction vehicle **14** is the sum of all the wheel tractive efforts.

FIG. **2** presents a simplified block diagram of an exemplary vehicle system with which the inventive subject matter may be used. A propulsion system **22** of FIG. **2** includes a variable speed prime mover or engine **24** mechanically coupled to a rotor of a dynamo electric machine **26** comprising, in this case, a 3-phase alternating current (AC) synchronous generator or alternator. The 3-phase voltages developed by alternator **26** are applied to AC input terminals of a conventional power rectifier bridge **28**. The direct current (DC) output of bridge **28** is coupled via a DC link **30** to a number of controlled inverters **32** and **34**, which invert the DC power to AC power at a selectable variable frequency. The inverters **32** and **34** employ high power gate turn-off devices which switch in and out of conduction in response to gating signals from a system controller **36** so as to invert the DC voltage on DC link **30** to controlled frequency AC voltage. In the illustrated embodiment, the AC power is electrically coupled in energizing relationship to each of a plurality of adjustable speed AC traction motors **38**, **40**, **42** and **44**. Prime mover **24**, alternator **26**, rectifier bridge **28** and inverters **32** and **34** are mounted on a platform of the traction vehicle **14**, illustrated as a diesel-electric locomotive. The platform is, in turn, supported on two trucks **46** and **48**, the first truck **46** having two axle-wheel sets **50** and **52** and the second truck **48** having two axle-wheel sets **54** and **56**.

Each of the traction motors **38**, **40**, **42**, and **44** is hung on a separate axle and its rotor is mechanically coupled, via conventional gearing, in driving relationship to the respective associated axle-wheel set. In the embodiment shown, the two motors **38** and **40** of axle wheel sets **50** and **52**, respectively, are electrically coupled in parallel with one another and receive power from inverter **34** while motors **42** and **44** are similarly coupled to inverter **32**. In some instances, however, it may be desirable to provide an inverter for each motor or to couple additional motors to a single inverter. The entire scope of the inventive subject matter is not limited to such 4-axle systems and is equally applicable to other systems, for example, such as 6-axle locomotives with six inverters each connected for powering a respective one of six traction motors each connected to respective ones of the six axles, or other systems.

Suitable current transducers **58** and voltage transducers **60** are used to provide current and voltage feedback signals which are respectively representative of the magnitudes of current and voltage applied to motors **38**, **40**, **42**, and **44**. Speed sensors **62** are used to provide speed signals representative of the rotational speeds W1-W4 in revolutions per minute (RPM) or proportional units of the motor shafts. These speed signals are converted to wheel speeds in accordance with an embodiment of the inventive subject matter. For simplicity, only single lines have been indicated for power flow, although it will be apparent that motors **38**, **40**, **42**, and **44** can be three phase motors so that each power line represents three lines in such applications.

The magnitude of output voltage and current supplied to rectifier bridge **28** is determined by the magnitude of excitation current supplied to the field windings of alternator **26** by a field controller **64** which may be a conventional phase controlled rectifier circuit, for alternator fields generally requiring DC excitation. The excitation current is set in response to an operator demand in a throttle **66** for vehicle speed by controller **36**, which is in turn responsive to actual speed as represented by signals W1-W4. Controller **36** converts the throttle command to a corresponding torque request for use in controlling motors **38**, **40**, **42**, and **44**. Since AC motor torque is proportional to rotor current and air gap flux, these quantities may be monitored. More commonly, other quantities, such as applied voltage, stator current and motor RPM, may be used to reconstruct motor torque in controller **36**. In an electrical braking or retarding mode of operation, inertia of the moving vehicle is converted into electrical energy by utilizing the traction motors as generators and motor voltage and current are controlled to set a desired braking effort.

Referring to FIG. **3**, a graphical representation is provided of relationships between adhesion and creep for different weather conditions, illustrating optimal creep levels for adhesion. Each curve illustrates an example of wheel-to-rail slipping or sliding in the motoring mode for three different weather conditions common to locomotive applications. The horizontal or the X-axis **74** of the adhesion-creep curves represents per unit creep values expressed as fractions and the vertical or the Y-axis **76** represents adhesion (friction coefficient) values also expressed as fractions. The three different weather conditions that were chosen for illustrative purposes are represented by "wet" curve **78**, "dry" curve **80**, and "dry with sand" curve **82**. It will be noted that the highest adhesion is available with a rail, which is both dry and sanded. As shown by the illustrated curve, the adhesion reaches a peak on the "dry and sanded" adhesion-creep curve at about a 0.05 per unit creep level and then gradually reduces as creep speed increases. Referring to the "dry" adhesion-creep curve, maximum adhesion is obtained at some value of per unit creep less than 0.1, while the "wet" adhesion-creep curve indicates that maximum adhesion is not realized until per unit creep obtains typically a value somewhere between 0.15 and 0.25. As shown in FIG. **3**, the best conditions for obtaining the greatest pulling force or tractive effort does not occur at zero creep, although the optimum creep level changes with conditions and can be expressed to change during the course of transport over any distance.

In general, it may be desirable to maintain per unit creep or creep speed at the point at which maximum adhesion occurs. It is thus possible to select the appropriate adhesion-creep curve based on observed weather conditions, and determine from this curve an ideal creep that must be achieved and maintained in order to achieve and maintain a maximum adhesion value. In addition, there are maximum and minimum allowable creep levels that are typically a function of vehicle speed, wheel tractive efforts, wheel speeds and the extent of axle torsional vibration. Additional constraints are also applied to decide the allowable creep. These factors and creep limits combine to allow sufficient non-zero creep levels for starting the locomotive from zero speed and to provide a fixed allowable creep level when the axle is rotating at the reference speed mode.

FIG. **4** is a functional block diagram illustrating an adhesion control system **84** residing in the respective controllers of inverters **32** or **34** for each axle shown in FIG. **2**, for separate creep control of each individual axle. The adhesion control system **84** comprises a torque increaser **88**, a creep modulator

90, a creep regulator **94**, an estimator **96**, and a torsional vibration detector **98**. One or more embodiments of the inventive subject matter may be implemented in conjunction with the system shown in FIG. **4**.

Tractive effort optimization in an adhesion control system may involve determination of an optimum allowable creep for the appropriate adhesion-creep curve and a feedback control system to track and maintain this optimum allowable creep within a range of minimum error. This function is realized by an adhesion control system **84** of FIG. **4**. This adhesion control system acts to ensure that the locomotive operates within a certain acceptable range around the peak of an appropriate adhesion-creep curve.

The torque increaser **88** measures traction system performance levels and determines the desired torque increaser state or operating mode for maximizing or increasing traction performance of each individual axle. The torque increaser **88** uses the best possible estimates/measurements of actual speeds and tractive efforts of both the wheels of any axle-wheel set obtained from the estimator **96** to estimate the traction performance level of the axle-wheel set and determine an appropriate torque increaser state.

The estimator **96** estimates the wheel speeds, wheel tractive efforts, and/or wheel creep values. If direct measurements of the wheel speeds and wheel tractive efforts are available, the estimator **96** can minimize the noise effects in these measurements. Moreover, wheel creep values may be estimated by subtracting the locomotive/ground speed estimate/measurement from the wheel speed estimates/measurements. Several methods can be used to estimate the locomotive speed such as, for example, GPS-based methods. The estimator **96** may be configured to additionally provide an estimate of the axle torsional torque.

The torsional vibration detector **98** digitally processes the wheel speed estimates/measurements, the difference in the wheel speed estimates/measurements of each axle, wheel tractive effort estimates/measurements and axle torsional torque estimate obtained from the estimator **96**, in addition to the motor torque feedback, motor speed, wheel strain, axle strain and dog-bone strain in order to detect an unacceptable level of torsional vibration in each axle. A functional block diagram of **98** is illustrated in more detail below.

The output of the torque increaser **88** along with a signal representative of the level of axle torsional vibration mode obtained from the torsional vibration detector **98** is provided to the creep modulator **90**. The creep modulator **90** processes these inputs to control the operating creep level of the locomotive gear and axle set described above in relation to FIG. **2**. The function of the creep modulator **90** is to modulate the allowable creep level for each axle between a maximum allowable creep level and a minimum allowable creep level. These maximum and minimum allowable creep levels are typically functions of vehicle speed, wheel tractive efforts, wheel speeds and the extent of axle torsional vibration. Additional constraints are also applied to decide the allowable creep. These factors and creep limits combine to allow sufficient non-zero creep levels for starting the locomotive from zero speed and to provide a fixed allowable creep level when the axle is functioning at the reference speed mode. An exemplary creep modulator is disclosed in U.S. Pat. No. 6,163,121, issued on Dec. 19, 2000 to General Electric Company (hereby incorporated into the present disclosure by reference).

The actual realized creep for each axle-wheel set is compared with the associated creep set point from creep modulator **90** at the comparator **92**. The error determined by the comparison is input to the creep regulator **94** whose objective is to keep this error as small as possible under all operating conditions through feedback control. The creep regulator **94** may be a proportional-plus-integral controller or a higher order controller designed to ensure stability of the creep regulation loop for every axle-wheel set, even when operating in the negative slope region of an adhesion characteristic curve. The output from the creep regulator **94** is a torque command that is fed to a torque regulator system **86** associated with the axle and which typically includes the associated torque regulation circuit, the power devices, and the electric motor illustrated in FIG. **2**. These motors drive the associated axle-wheel set through appropriate gearing as shown in **50**.

FIG. **5** is a schematic diagram of a control system **100**, according to an embodiment of the inventive subject matter described herein. The control system **100** is part of a vehicle traction system of a traction vehicle, such as the traction vehicle **14**. The control system **100** includes a traction motor system **102** having a traction motor and an inverter electrically connected to the traction motor. In FIG. **5**, the traction motor system **102** represents one or more traction motors and one or more inverters. The control system **100** generates signals for controlling the inverter to produce power waveforms for powering the traction motor. A wheel **104** is operably coupled to the traction motor. The control system **100** comprises a first control module **106** and a second control module **108**. (The modules described herein may comprise or represent electronic hardware and/or software, and may be part of a common controller card or similar electronics unit for motor control.)

The first control module **106** is configured to generate an excitation frequency **110** for the traction motor system **102**, based at least in part on one or more measured speeds **128** and a throttle command **122**. The measured speeds **128** can be associated with the traction motor and/or the wheel driven by the traction motor, and information of the measured speed may be provided by one or more sensors **126**. The measured speeds **128**, for example, may be or relate to a measure of wheel creep **112**. In one embodiment, the sensors **126** provide data representative of the speed at which the traction motor is rotating the wheel **104** and/or data representative of the speed at which the traction vehicle is moving along the route. For example, the sensors **126** can represent a rotation speed sensor and a movement speed sensor. The rotation speed sensor can be operatively connected with the wheel **104** and/or traction motor in order to determine how fast the wheel **104** is rotating and/or how fast the traction motor is operating, and to generate data representative of such speeds. The movement speed sensor can generate data representative of how fast the traction vehicle is moving along the route. By way of example, the movement speed sensor can include or use location data generated by a location determining system, such as a Global Positioning System receiver, in order to generate the data representative of the speed at which the traction vehicle moves along the route. This data representative of the measured speeds **128** can be communicated to a creep regulator **116** described below.

The first control module **106** includes a torque increaser **114**, the creep regulator **116**, and a torque regulator **118**. These components may be configured similarly to corresponding components in FIG. **4**. In an embodiment, one or more of the torque increaser **114**, creep regulator **116**, and/or torque regulator **118** may be provided as hardware and/or associated software components of the first control module **106**.

In one example, in operation, the first control module **106** receives an input signal **122** of desired tractive effort (e.g., power, torque, speed, or the like) that is sought to be produced by the propulsion system of the traction vehicle (e.g., from a vehicle control system), which incorporates or is generated based (at least in part) on a throttle command. The throttle command may be provided to the torque increaser **114** as the input signal **122** from a throttle (e.g., throttle **66**) of the vehicle control system, from a system that autonomously determines throttle settings for the traction vehicle (e.g., an energy management system that determines throttle and/or brake settings in order to cause the traction vehicle to follow a trip plan having operational settings of the vehicle that are designated as a function of time and/or distance along a trip in order to reduce at least one of emissions generated and/or fuel consumed by the traction vehicle during the trip), or from another input.

The torque increaser **114** generates an output signal **124** based on the input signal **122**. This output signal **124** can represent the amount of torque that corresponds to the desired tractive effort that is represented by the input signal **122**. For example, if the input signal **122** represent a desired power output from the propulsion system of the traction vehicle, then the torque increaser **114** can create the output signal **124** to represent the torque that is estimated or calculated to be needed to be produced by one or more of the traction motors in order for the propulsion system to actually generate the desired power output. If the input signal **122** represent a desired speed of the traction vehicle, then the torque increaser **114** can create the output signal **124** to represent the torque that is estimated or calculated to be needed to be produced by one or more of the traction motors in order for the propulsion system to actually generate sufficient output to cause the traction vehicle to travel at the desired speed. If the input signal **122** represents a desired torque output from the propulsion system of the traction vehicle, then the torque increaser **114** can create the output signal **124** to represent this torque. The output signal **124** may be generated without the torque increaser **114** knowing the wheel creep **112** of one or more wheels in one embodiment. The amount of torque that is represented by the output signal **124** can depend on one or more factors, such as a current speed of the traction vehicle, the wheel creep **112** of one or more wheels of the traction vehicle, the size (e.g., length and/or weight) of the vehicle, and the like.

The creep regulator **116** outputs a torque command **120** responsive to an output of the torque increaser **114** and wheel creep **112**. In one embodiment, the creep regulator **116** receives the wheel creep **112** directly from another module, such as a creep module **130** that receives the data representative of the rotation speed of the traction motor or wheel **104** and/or the data representative of the movement speed of the traction vehicle from the speed sensors **126**. Alternatively or additionally, the creep regulator **116** may calculate the wheel creep **112** based on the data received from the speed sensors **126**.

Responsive to the torque command **120** and possibly other inputs (such as the signal of desired torque form the vehicle control system, depending on how the module **106** is configured), the torque regulator **118** outputs an excitation frequency **110**. The excitation frequency **110** represents the frequency of the current that is to be supplied to the traction motor in order to power the traction motor and cause the traction motor to provide the desired tractive effort represented by the throttle command **122**. The excitation frequency **110** may change based on several factors, such as changes in the desired tractive effort (as input by an operator, energy management system, or the like), changes in the wheel creep **112** (as determined or received by the creep regulator **116**, where the torque regulator **118** can increase the excitation frequency for decreasing wheel creep **112** and/or decrease the excitation frequency for increasing wheel creep **112**), deterioration in the health and/or age of the traction motor (e.g., where an increased excitation frequency may be needed to cause an older and/or deteriorated traction motor to provide a desired tractive effort relative to a newer and/or healthier traction motor), and the like.

Due to, among other factors, changes in the wheel creep **112** as the traction vehicle moves, changes in the torque command **120**, and the like, the excitation frequency **110** that is output by the torque regulator **118** may change with respect to time. For example, the excitation frequency **110** may change at a relatively rapid pace due to detected changes in the wheel creep **112**. The excitation frequency **110** may be changed by the torque regulator **118** in order to ensure that the traction motor generates sufficient torque to satisfy the torque command **120** in light of the changes in the wheel creep **112** and/or other factors, even if the throttle command **122** remains unchanged or changes relatively little.

The second control module **108** receives the excitation frequency **110**. The second control module **108** is configured to limit a rate of change of the excitation frequency **110**. As described above, the excitation frequency **110** may change over time due to various factors in order to cause the traction motor to generate the torque that corresponds to the throttle command **122**. The second control module **108** may limit the rate of change in the excitation frequency responsive to the wheel creep **112** of the wheel **104** exceeding a wheel creep threshold **200** (see FIG. **6**). For example, in one embodiment, the second control module **108** may not limit the rate of change in the excitation frequency until the wheel creep **112** exceeds a non-zero and non-infinite wheel creep threshold **200**. Alternatively, the second control module **108** may always limit the rate of change in the excitation frequency, but the limits applied to the rates of change in the excitation frequency may be based on the wheel creep **112**.

In an embodiment, the second control module **108** compares information of the wheel creep **112** to the wheel creep threshold **200**, and if the wheel creep **112** exceeds the threshold **200**, the second control module **108**, limits or restricts the rate at which the excitation frequency can change. The wheel creep **112** can be provided to the second control module **108** by the first control module **106** (e.g., the torque regulator **116**). Alternatively or additionally, the second control module **108** can determine the wheel creep **112** based on the data provided by one or more of the speed sensors **126**, as described above. The limits applied to the rate of change in the excitation frequency can result in a change in wheel or motor speed information (as provided from the speed sensor **126** and indicative of and/or resulting from a forthcoming spike in wheel creep **112**) that would otherwise result in the first control module adding or increasing the excitation frequency, the second control module **108** may prevent or limit his addition to or increase in the excitation frequency.

The limit on the rate of change in the excitation frequency can be expressed as an absolute limit or a relative limit. For example, with respect to an absolute limit, the second control module **108** may not permit the excitation frequency to increase by more than a designated amount (e.g., a change in frequency) within a designated time period. With respect to a relative limit, the second control module **108** may not permit the excitation frequency to increase by more than a designated percentage of the excitation frequency within a designated time period. The limits applied by the second control module **108** may be customized to individual traction motors and/or traction vehicles. These limits may be hard-coded in the software of the system **100** and/or may be modified by an operator of the traction vehicle.

When a limit on the rate of change in the excitation frequency is being applied, the second control module **108** compares changes in the excitation frequency over time and determines an actual rate of change in the excitation frequency. This rate may be calculated as a different between previous and subsequent excitation frequencies divided by the time period between when the previous and subsequent excitation frequencies are determined by the torque regulator **118** and/or communicated to the second control module **108**. The second control module **108** compares the actual rate of change in the excitation frequency to the limit on the rate of change in the excitation frequency. If the actual rate does not exceed the limit, then the second control module **108** does not alter the excitation frequency output from the torque regulator **118**. As a result, the excitation frequency output from the torque regulator **118** is used as the frequency of the current that is supplied to the traction motor in order to power the motor to propel the vehicle.

If the actual rate does exceed the limit, however, then the second control module **108** can limit the excitation frequency that is output from the torque regulator **118** by altering the excitation frequency. In one embodiment, the second control module **108** alters the excitation frequency by keeping the excitation frequency as the same value as a previous excitation frequency. For example, the second control module **108** may change the excitation frequency to a frequency that is the same as the previous excitation frequency. As a result, the rate of change in the excitation frequency may be decreased to a value that is smaller than the limit. Alternatively, the second control module **108** may alter the excitation frequency by reducing the excitation frequency to another value that results in the rate of change in the excitation frequency being no greater than the limit on the rate of change in the excitation frequency. The excitation frequency that is output from the torque regulator **118** (as altered by the limit when applicable) is used as the frequency of the current that is supplied to the traction motor in order to power the motor to propel the vehicle.

The wheel creep threshold **200** can be based on the speed at which the traction vehicle is moving along the route. For example, at speeds below a designated threshold (such as a value that is indicative of a relatively low vehicle speed, such as less than 48 kilometers per hour, less than 32 kilometers per hour, less than 16 kilometers per hour, less than 8 kilometers per hour, and the like), the threshold wheel creep may be 3.5% (or another value). At speeds above this threshold, a larger threshold wheel creep may be used. If the detected wheel creep for a wheel-axle set exceeds this threshold, then the limit on the rate of change in excitation frequency supplied to the traction motor or motors associated with the same wheel-axle set may be applied.

The extent to which the rate of change of the excitation frequency is limited may be based on limiting a gain in the wheel creep. That is, the excitation frequency rate of change is limited to the extent to limit a gain in wheel creep. In one embodiment, the excitation frequency rate of change is restricted or limited to limit the wheel creep gain to no more than 1.61 kph/sec (e.g., 1 mph/sec).

In an embodiment, the rate of change of the excitation frequency is limited when the wheel speed is below a designated value (such as a value that is indicative of a relatively low vehicle speed, such as less than 48 kilometers per hour, less than 32 kilometers per hour, less than 16 kilometers per hour, less than 8 kilometers per hour, and the like). For example, at higher speeds (such as speeds at or above a designated threshold), the rate of change in the excitation frequency of the traction motors may not be limited but, at lower speeds (e.g., speeds below the designated threshold), the rate of change in the excitation frequency may be limited

The limit on the rate of change in the excitation frequency can be based on the speed at which the traction vehicle is traveling. For example, the limit on the rate of change in the excitation frequency can increase for faster speeds and decrease for slower speeds. As a result, the excitation frequency can vary at a greater rate within the designated limit at faster speeds of the traction vehicle. Conversely, at slower speeds, the rate of changes in the excitation frequency can be more restricted.

The limit on the allowed rate of change in the excitation frequency can continue to be applied to a traction motor or traction motors until the wheel creep that is monitored for the wheel-axle set or sets associated with the motor or motors falls below a designated, lower wheel creep threshold. This lower wheel creep threshold may be a non-zero threshold that differs from the threshold wheel creep used to determine when to apply the limit (also referred to as the upper threshold wheel creep). For example, if the threshold wheel creep used to determine when to apply the limit on the rate of change in the excitation frequency is 3.5% wheel creep, then the lower wheel creep threshold that is used to determine when to remove this limit can be another, lower value, such as 2.5% wheel creep (or another value). The lower wheel creep threshold may be different from the upper wheel creep threshold to prevent relatively brief, transitory variations in the wheel creep from causing the limit to be repeatedly and relatively rapidly applied and removed in an alternating manner. For example, if the upper and lower wheel creep thresholds were equivalent, then in some applications, the monitored wheel creep may vary above and below the thresholds relatively rapidly, thereby causing the limit to be relatively rapidly applied, removed, applied, removed, and so on, even though the wheel creep is not significantly decreasing. Making the lower wheel creep threshold be different and smaller than the upper wheel creep threshold may ensure that the limit on the rate of change in the excitation frequency continues to be applied until the wheel creep is actually decreased due to the application of the limit on the rate of allowable change in the excitation frequency.

FIG. **6** shows example wheel creep thresholds **200** for various adhesion curves **600**, **602**, **604**, **606**, **608**. The adhesion curves **600**, **602**, **604**, **606**, **608** are based on known wheel/surface interfaces for various weather conditions, as described above in regards to FIG. **3**. Threshold values may be selected as within three percent (3%) of the optimum creep for the highest level of adhesion (for a given interface and weather condition). For example, the upper threshold wheel creep that is used to determine when to apply the limit on the rate of change in the excitation frequency may be 3% of an optimum creep for a designated adhesion level based on the condition of the route (e.g., a dry route with sand applied to the route, a dry route with no sand applied to the route, a wet route with sand applied to the route, a wet route with no sand applied to the route, an oily route, and the like). The condition of the route may be selected by an operator of the traction vehicle.

Alternatively, the wheel creep threshold that is used to determine when to limit the rate of change in the excitation frequency can be a designated threshold, such as a threshold that is input by the operator and/or hard-coded into the system **100**, without reference to the condition of the route on which the traction vehicle is currently traveling.

Returning to the description of the control system **100** shown in FIG. **5**, the second control module **108** may additionally or alternatively limit or control the excitation frequencies of the traction motor based on changes in the torque generated by the traction motor. For example, the second control module **108** may monitor changes in the torque that is actually generated by the traction motor when the excitation frequencies of the traction motor change. If the second control module **108** identifies or determines that the torque decreases with increasing excitation frequencies, then the second control module **108** may determine that creep of the wheel being driven by the traction motor is increasing too quickly and/or that unacceptable wheel slip of the wheel is occurring or is more likely to occur (relative to the torque not decreasing with increasing excitation frequencies). In response to this determination, the second control module **108** may restrict further increases in the excitation frequencies. For example, the second control module **108** may prevent the excitation frequency from being increased further and/or may decrease the excitation frequency.

In an embodiment, the torque increaser **114** of the first control module **106** measures or estimates the torque generated by the traction motor in the traction motor system **102**. The torque increaser **114** may calculate the torque generated by the traction motor based on the RPMs or speed at which the wheel driven by the traction motor is rotating. The torque increaser **114** may calculate the torque using the RPMs of the motor and the horsepower of the motor and/or the watts of the motor. For example, the torque increaser **114** may determine the torque of the motor using one or more of the following relationships:

$$T = \frac{HP * 5252}{RPM} \qquad \text{(Eqn. \#1)}$$

$$HP = \frac{W}{746} \qquad \text{(Eqn. \#2)}$$

where T represents the measured torque of the motor, HP represents the horsepower of the motor, RPM represents the revolutions per minute of the motor, and W represents the watts of the motor. Optionally, another relationship or inputs may be used to determine the torque of the motor.

The torque increaser **114** monitors the torque of the motor and reports the torque and/or changes in the torque to the second control module **108**. The second control module **108** examines the torques received from the torque increaser **114** and monitors changes in the torques with respect to changes in the excitation frequency. The second control module **108** determines if the torques increase with increasing excitation frequency. For example, when the excitation frequency increases, the second control module **108** determines if the torque also increases. If the torque does not increase, then the second control module **108** may restrict the excitation frequencies in order to prevent the wheel from slipping or the creep of the wheel from increasing further.

FIG. **10** illustrates an example of torques **1000** generated by the motor and corresponding excitation frequencies supplied to the motor. The torques **1000** are shown alongside a horizontal axis **1002** representative of excitation frequencies supplied to the motor and a vertical axis **1004** representative of the torques measured by the torque increaser **114**. As shown in FIG. **10**, as the excitation frequencies increase, the torques **1000** generated by the motor increase up to a peak torque **1006** at a peak-associated excitation frequency **1008**. The peak torque **1006** may represent an upper torque produced by the motor at the peak-associated excitation frequency **1008**, but may not necessarily represent the maximum torque that can be generated by the motor. For example, under different or other circumstances (e.g., the vehicle traveling over a different grade of the route, different weather conditions, different vehicle speed, or the like), the motor may be capable of generating torque in excess of the peak torque **1006**.

In the illustrated example, when the excitation frequency of the current supplied to the motor increases above the frequency **1008** associated with the peak torque **1006**, the torques **1000** generated by the motor decrease. Further increases in the excitation frequency do not result in increases in the torque **1000** generated by the motor. This decrease in the torque **1000** with increasing excitation frequency may be a result of increased creep or wheel slip of the wheel that is rotated by the motor.

In response to detecting this decrease in torque **1000**, the second control module **108** may restrict further increases in the excitation frequency. For example, the second control module **108** may decrease the excitation frequency below the peak-associated excitation frequency **1008**. The second control module **108** may decrease the excitation frequency of the current supplied to the motor regardless of changes to the throttle settings of the vehicle that includes the motor. A manual or automatic increase in the throttle setting of the vehicle (which would otherwise cause the excitation frequency to be increased) may be disregarded, ignored, or otherwise not implemented by the control system **100**.

The second control module **108** may decrease the excitation frequency below the peak-associated frequency **1008**. For example, in response to the torque decreasing below the peak torque **1006** when the excitation frequency is increased above the peak-associated frequency **1008**, the second control module **108** may reduce the excitation frequency below the peak-associated frequency **1008** by at least a designated amount and/or to no greater than a lower designated frequency. The second control module **108** may decrease the excitation frequency even if the throttle is manually or automatically controlled to increase the excitation frequency or to have an excitation frequency that is greater than the lowered excitation frequencies that are implemented by the second control module **108**.

In one aspect, the second control module **108** reduces the excitation frequency below the peak-associated frequency **1008** at no faster than a relatively slow rate. For example, the second control module **108** may reduce the excitation frequency by setting the excitation frequency at different decreasing values over time, as opposed to immediately changing the excitation frequency to a lower designated excitation frequency. The second control module **108** may slowly reduce the excitation frequency to avoid abrupt changes in the excitation frequency causing abrupt changes in the velocity of the motor, wheel, and vehicle. Such abrupt changes can cause undesirable run-ins between adjacent or neighboring vehicles in the vehicle system.

The traction motors described herein may be induction motors or other AC motor types where the frequency of the applied voltage is a contributor to the developed motor torque. Examples of methods to measure creep, wheel speed, wheel tractive effort, etc. are found in commonly owned U.S. Pat. No. 7,285,926, issued Oct. 23, 2007, which is hereby incorporated by reference herein in its entirety.

FIG. **7** is a schematic diagram of a traction vehicle **700** in accordance with another embodiment. The traction vehicle **700** may be similar to the traction vehicle **14** (shown in FIG. **1**) and may be part of a larger vehicle system **10** (shown in FIG. **1**). The traction vehicle **700** includes a control system **702**, which may be similar to or represent the control system **100** (shown in FIG. **5**). A propulsion system **704** of the vehicle

700 represents the throttle, traction motors, inverters, axles, gears, and the like, that are used to control propulsion and breaking of the vehicle **700**.

In the illustrated embodiment, the traction vehicle **700** includes a friction modifying system **706**. The friction modifying system **706** includes or is connected with a friction modifying substance applicator **708**, which applies one or more friction modifying substances to the route **12** in order to change a friction coefficient of the route **12** and/or adhesion of wheels **710** of the vehicle **700** to the route **12**. The friction modifying substances can include sand, air, lubricant (e.g., oil), or other materials that increase or decrease the adhesion of the wheels **710** to the route **12**.

The friction modifying system **708** can include one or more processors, controllers, and the like, along with associated circuitry, for controlling when the applicator **708** applies the friction modifying substances to the route **12**. In one embodiment, the friction modifying system **708** autonomously directs the applicator **708** to apply a friction modifying substance to the route **12** in response to the measured wheel creep **112** (shown in FIG. **5**) of one or more wheels **710** of the vehicle **700**. For example, when the wheel creep **112** approaches (e.g., comes within a designated amount of) the wheel creep setpoint or threshold at which the rate of change in excitation frequency is limited, the friction modifying system **708** can autonomously direct the applicator to apply one or more friction modifying substances that increase the friction coefficient of the interface between the route **12** and the wheels **710**, such as air or sand. The friction modifying system **708** can autonomously attempt to increase the adhesion between the wheels **710** and the route **12** in order to prevent or delay the increase of the wheel creep **112** to the threshold at which the rate of change in excitation frequency of the current supplied to the traction motor is limited. Alternatively or additionally, the friction modifying system **708** can autonomously apply the friction modifying substance to the route **12** in response to the wheel creep **112** exceeding the threshold (and the rate of change in excitation frequency being limited). For example, once the limit on the rate of change in excitation frequency is applied, the friction modifying system **708** can attempt to increase the adhesion of the wheels **710** to the route **12** in order to reduce the time period that the limit on the rate of change in excitation frequency is applied.

FIG. **8** is a flowchart of one embodiment of a method **800** for controlling a traction motor. The method **800** may be used to control the excitation frequencies of current supplied to a traction motor. In a traction vehicle having multiple traction motors and/or axle-wheel sets connected to multiple traction motors, the method **800** may be individually applied to each of the traction motors such that different traction motors in the same vehicle may have differently controlled excitation frequencies.

At **802**, a throttle command is received from a throttle device. The throttle command may represent the tractive effort that is manually or autonomously requested to be provided by one or more traction motors of the vehicle. The throttle device that is used to provide the throttle command may be a throttle lever, pedal, button, touchscreen, dial, energy management system, or the like.

At **804**, the torque that is needed from a traction motor to provide the requested tractive effort is determined. This torque may be determined from one or more factors, such as the current speed of the vehicle, the size of the vehicle, the wheel creep of one or more wheels of the vehicle, and the like, as described above.

At **806**, wheel creep of the vehicle is monitored. For example, the wheel creep of one or more wheels of the vehicle can be measured as the vehicle travels. The wheel creep can be measured in a variety of manners, including by measuring a difference between the angular velocity of the outer perimeter of the wheel (which may be based on the movement speed of the vehicle along a route) and the rotational velocity at which the traction motor is rotating the wheel. The wheel creep can be monitored on a periodic, continual, or as-prompted basis during travel of the vehicle.

At **808**, a determination is made as to whether the wheel creep exceeds a wheel creep threshold. As described above, the wheel creep threshold may be based on a wheel creep setpoint that represents a wheel creep that will or is likely to result in the wheel losing adhesion to the route and slipping (e.g., moving relative to the route). The wheel creep threshold may be a fraction of the setpoint so that the comparison of the wheel creep to the threshold indicates whether the wheel creep is approaching the threshold.

If the wheel creep does not exceed the threshold, then the wheel creep may not be approaching the wheel creep associated with break-away between the wheel and the route (and slippage of the wheel on the route). As a result, the rate of change in excitation frequencies applied to the traction motor may not need to be limited. Consequently, flow of the method **800** may proceed to **810**.

At **810**, an excitation frequency of the current supplied to the traction motor is determined. This excitation frequency may be the frequency of current that causes the motor to provide the torque that is needed to provide the tractive effort requested by the throttle command. At **812**, the current is supplied to the traction motor at the excitation frequency. The motor is powered with the current and may change speeds based on the excitation frequency to alter the amount of torque provided by the motor.

Returning to the decision at **808**, if the wheel creep exceeds the threshold, then the wheel creep may be approaching a wheel creep associated with break-away between the wheel and the route. As a result, the rate of change in excitation frequencies applied to the traction motor may need to be limited. Consequently, flow of the method **800** may proceed to **814**.

At **814**, a limit on the rate of change in the excitation frequency is applied. This limit can prevent the excitation frequency from changing too drastically and causing an increase in the wheel creep and/or cause wheel slip between a wheel and the route.

At **816**, the excitation frequency of the current supplied to the traction motor is determined. This excitation frequency may be the frequency of current that causes the motor to provide the torque that is needed to provide the tractive effort requested by the throttle command.

At **818**, a determination is made as to whether a rate of change in the excitation frequency exceeds the limit. For example, the change in excitation frequencies (e.g., from a previous excitation frequency to the excitation frequency determined at **816**) over time is compared to the limit. If the rate of change in excitation frequencies exceeds the limit, then the excitation frequency may be increasing at such a rapid rate that the wheel creep is likely to further increase and/or cause wheel slip. As a result, flow of the method **800** continues to **820**.

At **820**, an excitation frequency other than the excitation frequency that is determined at **818** is used for the current supplied to power the traction motor. For example, and as described above, the excitation frequency determined at **816** may be changed to a previous excitation frequency or otherwise reduced so that the rate of change in the excitation frequency remains at or below the limit. The current is supplied to the traction motor at the changed excitation frequency.

Returning to the decision made at **818**, if the rate of change in excitation frequencies does not exceed the limit, then the excitation frequency may not be increasing at too rapid rate of a rate. As a result, flow of the method **800** continues to **822**.

At **822**, current is supplied to the traction motor at the excitation frequency that is determined at **816**. As described above, this current powers the traction motor to provide torque that is less likely to increase wheel creep and/or is less likely to cause wheel slip.

The limit on the rate of change in excitation frequency may continue to be applied until the wheel creep is reduced below a threshold. As described above, the threshold that is used to determine when to remove this limit may be lower than the threshold used to determine when to apply the limit. Using two different limits can reduce instances of the limit being alternatively applied and removed in a relatively rapid manner. Additionally or alternatively, the limit may continue to be applied until the wheel creep remains below the threshold used to determine when to apply the limit for at least a designated time period.

FIG. **9** is a flowchart of an embodiment of a method **900** for controlling a traction motor. The method **900** may be used to control the excitation frequencies of current supplied to a traction motor. In a traction vehicle having multiple traction motors and/or axle-wheel sets connected to multiple traction motors, the method **900** may be individually applied to each of the traction motors such that different traction motors in the same vehicle may have differently controlled excitation frequencies.

At **902**, a throttle command is received from a throttle device. The throttle command may represent the tractive effort that is manually or autonomously requested to be provided by one or more traction motors of the vehicle. The throttle device that is used to provide the throttle command may be a throttle lever, pedal, button, touchscreen, dial, energy management system, or the like.

At **904**, the torque that is needed from a traction motor to provide the requested tractive effort is determined. This torque may be determined from one or more factors, such as the current speed of the vehicle, the size of the vehicle, the wheel creep of one or more wheels of the vehicle, and the like, as described above.

At **906**, wheel creep of the vehicle is monitored. For example, the wheel creep of one or more wheels of the vehicle can be measured as the vehicle travels. The wheel creep can be measured in a variety of manners, including by measuring a difference between the angular velocity of the outer perimeter of the wheel (which may be based on the movement speed of the vehicle along a route) and the rotational velocity at which the traction motor is rotating the wheel. The wheel creep can be monitored on a periodic, continual, or as-prompted basis during travel of the vehicle.

At **908**, a determination is made as to whether the wheel creep exceeds a wheel creep threshold. As described above, the wheel creep threshold may be based on a wheel creep setpoint that represents a wheel creep that will or is likely to result in the wheel losing adhesion to the route and slipping (e.g., moving relative to the route). The wheel creep threshold may be a fraction of the setpoint so that the comparison of the wheel creep to the threshold indicates whether the wheel creep is approaching the threshold.

If the wheel creep does not exceed the threshold, then the wheel creep may not be approaching the wheel creep associated with break-away between the wheel and the route (and slippage of the wheel on the route). As a result, the rate of change in excitation frequencies applied to the traction motor may not need to be limited. Consequently, flow of the method **900** may proceed to **910**.

At **910**, an excitation frequency of the current, supplied to the traction motor is determined. This excitation frequency may be the frequency of current that causes the motor to provide the torque that is needed to provide the tractive effort requested by the throttle command. At **912**, the current is supplied to the traction motor at the excitation frequency. The motor is powered with the current and may change speeds based on the excitation frequency to alter the amount of torque provided by the motor.

Returning to the decision at **908**, if the wheel creep exceeds the threshold, then the wheel creep may be approaching a wheel creep associated with break-away between the wheel and the route. As a result, the rate of change in excitation frequencies applied to the traction motor may need to be limited. Consequently, flow of the method **900** may proceed to **914**.

At **914**, a limit on the rate of change in the excitation frequency is applied. This limit can prevent the excitation frequency from changing too drastically and causing an increase in the wheel creep and/or cause wheel slip between a wheel and the route.

At **916**, the excitation frequency of the current supplied to the traction motor is determined. This excitation frequency may be the frequency of current that causes the motor to provide the torque that is needed to provide the tractive effort requested by the throttle command.

At **918**, a determination is made as to whether a rate of change in the excitation frequency exceeds the limit. For example, the change in excitation frequencies (e.g., from a previous excitation frequency to the excitation frequency determined at **916**) over time is compared to the limit. If the rate of change in excitation frequencies exceeds the limit, then the excitation frequency may be increasing at such a rapid rate that the wheel creep is likely to further increase and/or cause wheel slip. As a result, flow of the method **900** continues to **920**.

At **920**, an excitation frequency other than the excitation frequency that is determined at **918** is used for the current supplied to power the traction motor. For example, and as described above, the excitation frequency determined at **916** may be changed to a previous excitation frequency or otherwise reduced so that the rate of change in the excitation frequency remains at or below the limit. The current is supplied to the traction motor at the changed excitation frequency.

Returning to the decision made at **918**, if the rate of change in excitation frequencies does not exceed the limit, then the excitation frequency may not be increasing at too rapid rate of a rate. As a result, flow of the method **900** continues to **922**.

At **922**, current is supplied to the traction motor at the excitation frequency that is determined at **916**. As described above, this current powers the traction motor to provide torque that is less likely to increase wheel creep and/or is less likely to cause wheel slip.

At **924**, the torque produced by the traction motor is monitored. The torque may be periodically monitored, monitored when the excitation frequency changes, monitored on automatic or operator demand, or otherwise tracked. The torque is monitored in order to ensure that the torque is changing as expected with changes in the excitation frequency.

At **926**, a determination is made as to whether the torque produced by the motor is increasing when the excitation frequency of the current supplied to the motor increases. As described above, the torque produced by the motor is expected to increase when the excitation frequency of the current supplied to the motor increases. If the torque does not increase when the excitation frequency is increased, then the static or decreasing torque may be indicative of the wheel that is driven by the motor slipping relative to the route. If the torque is not increasing with increasing excitation frequency, then flow of the method **900** proceeds to **928**.

Conversely, if the torque is increasing with an increase in the excitation frequency, then flow of the method **900** returns to **902**. The method **900** may return to **902** so that another throttle command may be received and operation of the method **900** is repeated one or more times.

At **928**, increases in the excitation frequency are restricted. In one aspect, an increase in the excitation frequency that was recently implemented at **912**, **920**, or **922** is reversed, such as by decreasing the excitation frequency to a value less than the excitation frequency that was recently implemented at **912**, **920**, **922**. The excitation frequency may be decreased by a greater amount than the increase that was recently implemented, such as by decreasing the excitation frequency at a relatively slow rate to a lower value than prior to the recent increase in excitation frequency. Optionally, the excitation frequency that was implemented at **912**, **920**, or **922** may not be reversed, but a subsequent increase in the excitation frequency may be disregarded and the excitation frequency decreased. The excitation frequency may be reduced to prevent or reduce wheel slip, as described above.

Flow of the method **900** may then return to **902** for an additional throttle commend to be received. The method **900** may proceed in a loop-wise manner one or more times to control and limit changes in the excitation frequencies of current supplied to a motor to reduce and/or prevent wheel slip, and/or to control wheel creep.

In an embodiment, a control method (e.g., for controlling a traction motor of a vehicle) includes determining wheel creep of a wheel operably coupled to the traction motor and, based on the determined wheel creep, limiting a rate of change of an excitation frequency of current that is applied to the traction motor to drive the wheel.

In one aspect, the rate of change of the excitation frequency is limited if the wheel creep exceeds a wheel creep threshold.

In one aspect, the rate of change of the excitation frequency is limited to a first rate of change value that is less than a second rate of change value sought to be applied to the traction motor by a regulator module according to the wheel creep. The regulator module includes at least one of a creep regulator or a torque regulator.

In one aspect, the wheel creep is determined at least in part based on a speed of the traction motor.

In one aspect, limiting the rate of change of the excitation frequency limits wheel creep gain of the wheel.

In one aspect, the wheel creep gain is limited to no more than 1.61 kph/sec.

In one aspect, the rate of change is limited to limit wheel creep gain of the wheel to no more than 1.61 kph/sec.

In one aspect, determining the wheel creep and limiting the rate of change of the excitation frequency are carried out independently for each of a plurality of wheel and traction motor pairs of the vehicle.

In one aspect, determining the wheel creep and limiting the rate of change of the excitation frequency are carried out by an electronic control module configured to generate signals for controlling a traction inverter to power the traction motor.

In one aspect, the rate of change of the excitation frequency is limited when at least one of a speed of the wheel or a speed of a vehicle is below a designated value.

In an embodiment, a control method (e.g., for controlling a traction motor of a vehicle) includes determining whether wheel creep of a wheel operably coupled to the traction motor exceeds a wheel creep threshold and limiting a rate of change of an excitation frequency applied to the traction motor to drive the wheel when the wheel creep exceeds the wheel creep threshold.

In one aspect, the control method also includes applying the excitation frequency to the traction motor to drive the wheel. Limiting the rate of change of the excitation frequency can include restricting the rate at which the excitation frequency can change responsive to the wheel creep of the wheel exceeding the wheel creep threshold.

In one aspect, the control method also includes applying the excitation frequency and monitoring the wheel creep of the wheel.

In an embodiment, a control method (e.g., for controlling a traction motor of a vehicle) includes determining whether a wheel driven by the traction motor has accelerated away from a creep setpoint by at least a threshold and controlling an excitation frequency applied to the traction motor to reduce accelerating torque delivered by the motor to the wheel when the wheel has accelerated away from the creep setpoint by at least the threshold.

In one aspect, controlling the excitation frequency comprises limiting a rate of change of the excitation frequency.

In an embodiment, a control system (e.g., for a vehicle having a traction motor) includes first and second control modules. The first control module is configured to generate an excitation frequency of a current supplied to a traction motor of a traction motor system, based at least in part on a throttle command and a speed associated with one of the traction motor or a wheel driven by the traction motor. The second control module is configured to limit a rate of change of the excitation frequency responsive to a wheel creep of the wheel exceeding a wheel creep threshold.

In one aspect, the second control module is configured to limit the rate of change of the excitation frequency to a first rate of change value that is less than a second rate of change value sought to be applied to the traction motor by the first control module according to the wheel creep.

In one aspect, the second control module is configured to limit the rate of change of the excitation frequency in order to limit wheel creep gain of the wheel.

In one aspect, the first control module is configured to determine the wheel creep and the second control module is configured to limit the rate of change of the excitation frequency independently for each of a plurality of wheel and traction motor pairs of a vehicle.

In one aspect, the second control module is configured to limit the rate of change of the excitation frequency when at least one of a speed of the wheel or a speed of a vehicle is below a designated value.

In an embodiment, a control method includes monitoring changes in torque produced by a traction motor when an excitation frequency of current supplied to the traction motor changes, determining if the torque produced by the traction motor decreases when the excitation frequency of the current supplied to the traction motor increases, and responsive to the torque produced by the traction motor decreasing when the excitation frequency increases, preventing the excitation frequency of the current supplied to the traction motor from increasing further.

In one aspect, one or more of monitoring the changes in the torque, determining if the torque decreases, and/or preventing the excitation frequency from increasing further is performed by one or more processors.

In one aspect, the excitation frequency is prevented from increasing further by reducing the excitation frequency responsive to the torque decreasing when the excitation frequency is increased.

In one aspect, the torque produced by the traction motor increases to a peak torque when the excitation frequency increases to a peak-associated excitation frequency and the torque decreases below the peak torque when the excitation frequency is increased above the peak-associated excitation frequency. The excitation frequency is prevented from increasing further by reducing the excitation frequency to a value below the peak-associated excitation frequency.

In one aspect, preventing the excitation frequency from increasing further includes disregarding manually or automatically selected increases in a throttle setting of a vehicle that includes the traction motor that would otherwise cause the excitation frequency to increase.

In one aspect, the method also includes determining wheel creep of a wheel operably coupled to the traction motor and, based on the wheel creep that is determined, limiting a rate of change of the excitation frequency of current that is supplied to the traction motor.

In one aspect, the rate of change of the excitation frequency is limited to a first rate of change value that is less than a second rate of change value sought to be applied to the traction motor by a regulator module according to the wheel creep. The regulator module includes at least one of a creep regulator or a torque regulator.

In one aspect, monitoring the changes in the torque, determining if the torque decreases when the excitation frequency increases, and preventing the excitation frequency from increasing further are carried out independently for each of a plurality of wheel and traction motor pairs of a vehicle.

In an embodiment, a control system (e.g., for a vehicle) includes first and second control modules. The first control module is configured to control an excitation frequency of a current supplied to a traction motor of a traction motor system, based at least in part on a throttle command and a speed associated with one of the traction motor or a wheel driven by the traction motor. The second control module is configured to monitor changes in torque produced by the traction motor when the excitation frequency changes and determine if the torque produced by the traction motor decreases when the excitation frequency increases. The second control module is configured to prevent the excitation frequency of the current supplied to the traction motor from increasing further responsive to the torque decreasing when the excitation frequency increases.

In one aspect, the second control module is configured to prevent the excitation frequency from increasing further by reducing the excitation frequency responsive to the torque decreasing when the excitation frequency is increased.

In one aspect, the torque produced by the traction motor increases to a peak torque when the excitation frequency increases to a peak-associated excitation frequency and the torque decreases below the peak torque when the excitation frequency is increased above the peak-associated excitation frequency. The second control module is configured to prevent the excitation frequency from increasing further by reducing the excitation frequency to a value below the peak-associated excitation frequency.

In one aspect, the second control module is configured to prevent the excitation frequency from increasing further by disregarding manually or automatically selected increases in a throttle setting of a vehicle that includes the traction motor that would otherwise cause the excitation frequency to increase.

In one aspect, the first control module is configured to determine wheel creep of the wheel driven by the traction motor and the second control module is configured to limit a rate of change of the excitation frequency based on the wheel creep that is determined.

In one aspect, the second control module is configured to limit the rate of change of the excitation frequency to a first rate of change value that is less than a second rate of change value sought to be applied to the traction motor by a regulator module according to the wheel creep. The regulator module includes at least one of a creep regulator or a torque regulator.

In one aspect, the first control module is configured to control the excitation frequency and the second control module is configured to prevent the excitation frequency from increasing further independently for each of a plurality of wheel and traction motor pairs of a vehicle.

In an embodiment, a method (e.g., for controlling a vehicle) includes receiving changes to a throttle setting of a vehicle. The changes to the throttle setting change torque generated by a first traction motor in rotating a first wheel of the vehicle in order to propel the vehicle along a route. The method also includes determining excitation frequencies of electric current that is supplied to the first traction motor in order to power the first traction motor. The excitation frequencies are determined from the changes to the throttle setting of the vehicle. The method further includes monitoring changes in the torque generated by the first traction motor caused by changes in the excitation frequencies of the electric current supplied to the first traction motor and determining when increases in the excitation frequencies result in decreases in the torque generated by the first traction motor. The method also includes, responsive to determining that the increases in the excitation frequencies result in the decreases in the torque generated by the first traction motor, reducing the excitation frequencies of the electric current supplied to the first traction motor.

In one aspect, the torque generated by the first traction motor increases to a peak torque when the excitation frequencies increase to a peak-associated excitation frequency and the torque decreases below the peak torque when the excitation frequencies increase above the peak-associated excitation frequency. The excitation frequencies are reduced to a value below the peak-associated excitation frequency responsive to determining that the increases in the excitation frequencies result in the decreases in the torque generated by the first traction motor.

In one aspect, reducing the excitation frequencies includes disregarding manually or automatically selected increases in the throttle setting of the vehicle that would otherwise cause the excitation frequencies to increase.

In one aspect, the method also includes determining wheel creep of the first wheel operably coupled to the first traction motor and based on the wheel creep that is determined, limiting a rate of change of the excitation frequencies of the electric current that is supplied to the first traction motor.

In one aspect, the rate of change of the excitation frequencies is limited to a first rate of change value that is less than a second rate of change value sought to be applied to the first traction motor by a regulator module according to the wheel creep. The regulator module includes at least one of a creep regulator or a torque regulator.

In one aspect, the vehicle includes the first traction motor configured to drive the first wheel and at least a second traction motor configured to drive at least a second wheel. The method can also include monitoring changes in torque generated by the at least the second traction motor caused by changes in excitation frequencies of electric current supplied to the at least the second traction motor independent of the first traction motor, determining when increases in the excitation frequencies of the electric current supplied to the at least the second traction motor result in decreases in the torque generated by the at least the second traction motor independent of the first traction motor, and responsive to determining that the increases in the excitation frequencies of the electric current supplied to the at least the second traction motor result in the decreases in the torque generated by the at least the second traction motor, reducing the excitation frequencies of the electric current supplied to the at least the second traction motor independent of the first traction motor.

In the appended claims, the terms "including" and "having" are used as the plain-language equivalents of the term "comprising"; the term "in which" is equivalent to "wherein." Moreover, in the following claims, the terms "first," "second," "third," "upper," "lower," "bottom," "top," etc, are used merely as labels, and are not intended to impose numerical or positional requirements on their objects. Further, the limitations of the following claims are not written in means-plus-function format and are not intended to be interpreted based on 35 U.S.C. §112, sixth paragraph, unless and until such claim limitations expressly use the phrase "means for" followed by a statement of function void of further structure. As used herein, an element or step recited in the singular and proceeded with the word "a" or "an" should be understood as not excluding plural of said elements or steps, unless such exclusion is explicitly stated. Furthermore, references to "one embodiment" of the inventive subject matter are not intended to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features. Moreover, unless explicitly stated to the contrary, embodiments "comprising," "including," or "having" an element or a plurality of elements having a particular property may include additional such elements not having that property. Moreover, certain embodiments may be shown as having like or similar elements, however, this is merely for illustration purposes, and such embodiments need not necessarily have the same elements unless specified in the claims.

As used herein, the terms "may" and "may be" indicate a possibility of an occurrence within a set of circumstances; a possession of a specified property, characteristic or function; and/or qualify another verb by expressing one or more of an ability, capability, or possibility associated with the qualified verb. Accordingly, usage of "may" and "may be" indicates that a modified term is apparently appropriate, capable, or suitable for an indicated capacity, function, or usage, while taking into account that in some circumstances the modified term may sometimes not be appropriate, capable, or suitable. For example, in some circumstances an event or capacity can be expected, while in other circumstances the event or capacity cannot occur—this distinction is captured by the terms "may" and "may be."

Although the inventive subject matter has been described above, it should be understood that the same is intended by way of illustration and example only and is not to be taken by way of limitation. Accordingly, the spirit and scope of the inventive subject matter are to be limited only by the terms of the appended claims. Moreover, while only certain features of the invention have been illustrated and described herein, many modifications and changes will occur to those of ordinary skill in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the inventive subject matter.

The invention claimed is:

1. A control method comprising:

using a torque increaser, monitoring changes in torque produced by a traction motor when an excitation frequency of electric current supplied to the traction motor changes;

using a creep modulator, determining if the torque produced by the traction motor decreases when the excitation frequency of the current supplied to the traction motor increases; and

using the creep modulator and responsive to the torque produced by the traction motor decreasing when the excitation frequency increases, preventing the excitation frequency of the current supplied to the traction motor from increasing further.

2. The method of claim **1**, wherein the excitation frequency is prevented from increasing further by reducing the excitation frequency responsive to the torque decreasing when the excitation frequency is increased.

3. The method of claim **1**, wherein the torque produced by the traction motor increases to a peak torque when the excitation frequency increases to a peak-associated excitation frequency and the torque decreases below the peak torque when the excitation frequency is increased above the peak-associated excitation frequency, and wherein the excitation frequency is prevented from increasing further by reducing the excitation frequency to a value below the peak-associated excitation frequency.

4. The method of claim **1**, wherein preventing the excitation frequency from increasing further includes disregarding manually or automatically selected increases in a throttle setting of a vehicle that includes the traction motor that would otherwise cause the excitation frequency to increase.

5. The method of claim **1**, further comprising determining wheel creep of a wheel operably coupled to the traction motor and based on the wheel creep that is determined, limiting a rate of change of the excitation frequency of current that is supplied to the traction motor.

6. The method of claim **5**, wherein the rate of change of the excitation frequency is limited to a first rate of change value that is less than a second rate of change value sought to be applied to the traction motor by a regulator module according to the wheel creep, the regulator module comprising at least one of a creep regulator or a torque regulator.

7. The method of claim **1**, wherein monitoring the changes in the torque, determining if the torque decreases when the excitation frequency increases, and preventing the excitation frequency from increasing further are carried out independently for each of a plurality of wheel and traction motor pairs of a vehicle.

8. A system comprising:

a creep modulator configured to control an excitation frequency of a current supplied to a traction motor of a traction motor system, based at least in part on a throttle command and a speed associated with one of the traction motor or a wheel driven by the traction motor; and

a torque increaser configured to monitor changes in torque produced by the traction motor when the excitation frequency changes and determine if the torque produced by the traction motor decreases when the excitation frequency increases, wherein the creep modulator is configured to prevent the excitation frequency of the current supplied to the traction motor from increasing further responsive to the torque decreasing when the excitation frequency increases.

9. The system of claim **8**, wherein the creep modulator is configured to prevent the excitation frequency from increasing further by reducing the excitation frequency responsive to the torque decreasing when the excitation frequency is increased.

10. The system of claim **8**, wherein the torque produced by the traction motor increases to a peak torque when the excitation frequency increases to a peak-associated excitation frequency and the torque decreases below the peak torque when the excitation frequency is increased above the peak-associated excitation frequency, and wherein the creep modulator is configured to prevent the excitation frequency from increasing further by reducing the excitation frequency to a value below the peak-associated excitation frequency.

11. The system of claim **8**, wherein the creep modulator is configured to prevent the excitation frequency from increasing further by disregarding manually or automatically selected increases in a throttle setting of a vehicle that includes the traction motor that would otherwise cause the excitation frequency to increase.

12. The system of claim **8**, further comprising an estimator configured to determine wheel creep of the wheel driven by the traction motor and the creep modulator is configured to limit a rate of change of the excitation frequency based on the wheel creep that is determined.

13. The system of claim **12**, wherein the creep modulator is configured to limit the rate of change of the excitation frequency to a first rate of change value that is less than a second rate of change value sought to be applied to the traction motor according to the wheel creep.

14. The system of claim **8**, wherein the torque increaser is configured to control the excitation frequency and the creep modulator is configured to prevent the excitation frequency from increasing further independently for each of a plurality of wheel and traction motor pairs of a vehicle.

15. A method comprising:

using a torque increaser, receiving changes to a throttle setting of a vehicle, the changes to the throttle setting changing torque generated by a first traction motor in rotating a first wheel of the vehicle in order to propel the vehicle along a route;

using a creep modulator, determining excitation frequencies of electric current that is supplied to the first traction motor in order to power the first traction motor, the excitation frequencies determined from the changes to the throttle setting of the vehicle;

using the creep modulator, monitoring changes in the torque generated by the first traction motor caused by changes in the excitation frequencies of the electric current supplied to the first traction motor;

using the creep modulator, determining when increases in the excitation frequencies result in decreases in the torque generated by the first traction motor; and

using the creep modulator and responsive to determining that the increases in the excitation frequencies result in the decreases in the torque generated by the first traction motor, reducing the excitation frequencies of the electric current supplied to the first traction motor.

16. The method of claim **15**, wherein the torque generated by the first traction motor increases to a peak torque when the excitation frequencies increase to a peak-associated excitation frequency and the torque decreases below the peak torque when the excitation frequencies increase above the peak-associated excitation frequency, and wherein the excitation frequencies are reduced to a value below the peak-associated excitation frequency responsive to determining that the increases in the excitation frequencies result in the decreases in the torque generated by the first traction motor.

17. The method of claim **15**, wherein reducing the excitation frequencies includes disregarding manually or automatically selected increases in the throttle setting of the vehicle that would otherwise cause the excitation frequencies to increase.

18. The method of claim **15**, further comprising determining wheel creep of the first wheel operably coupled to the first traction motor and based on the wheel creep that is determined, limiting a rate of change of the excitation frequencies of the electric current that is supplied to the first traction motor.

19. The method of claim **18**, wherein the rate of change of the excitation frequencies is limited to a first rate of change value that is less than a second rate of change value sought to be applied to the first traction motor by a regulator module according to the wheel creep, the regulator module comprising at least one of a creep regulator or a torque regulator.

20. The method of claim **15**, wherein the vehicle includes the first traction motor configured to drive the first wheel and at least a second traction motor configured to drive at least a second wheel, and further comprising monitoring changes in torque generated by the at least the second traction motor caused by changes in excitation frequencies of electric current supplied to the at least the second traction motor independent of the first traction motor, determining when increases in the excitation frequencies of the electric current supplied to the at least the second traction motor result in decreases in the torque generated by the at least the second traction motor independent of the first traction motor, and responsive to determining that the increases in the excitation frequencies of the electric current supplied to the at least the second traction motor result in the decreases in the torque generated by the at least the second traction motor, reducing the excitation frequencies of the electric current supplied to the at least the second traction motor independent of the first traction motor.

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